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Schedule time compression : a method for project time-cost optimization.

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SCHEDULE TIME COMPRESSION; A METHOD FOR PROJECT TIME-COST OPTIMIZATION.

by

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SCHEDULE TIME COMPRESSION:
A METHOD FOR PROJECT TIME-COST OPTIMIZATION

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CHAPTER I

INTRODUCTION

Background

Management is the act of planning, organizing, coordinating, controlling, and supervising a project or activity toward the accomplishment of an end or objective. There are essentially three individual responsibilities that managers have in performing these management functions. First, the manager must choose or recognize a specific goal or objective. Second, he must organize all available resources by means of a plan to achieve his objective. Third, he must measure actual performance in terms of the plan in order to effectively manipulate his resources. To assist in performing these management functions in our highly technological society, there have been developed scientific management tools and techniques.

One of the most important advances in the search for better methods for use by managers to perform their responsibilities has been the introduction of network-based scheduling systems such as PERT (Program Evaluation and Review Technique) and CPM (Critical Path Method).

With the advent of network-based scheduling systems

project management has undergone considerable refinement.[1] Previously, as long as projects remained small, and the interdependency between tasks comprising the project was small, Gantt charting techniques were sufficient. These techniques are still sufficient for many projects. However, the day of project control through only a manager's intuition is over. When the need for better management techniques became so accute as to hinder organizational goals, managers and academicians began to develop a management science.

With the emergence of network-based scheduling systems such as PERT and CPM, management gained effective planning and controlling techniques. In these systems, emphasis is placed upon time for the purpose of planning and scheduling men and other resources for project completion. With respect to planning and scheduling, the project manager is concerned with developing an optimal plan of tasks comprising a project with all its interrelationships. He is concerned with scheduling these tasks in some optimal time frame, and he desires to effectively control the schedule. For the most part, network scheduling systems have concentrated on the time parameter, and, to an extent, have neglected the cost parameter that evolves when monitoring the expenditure of time and money

[1] The management systems discussed herein relate primarily to project management; that is, the responsibility for the integration of all functional activities required for the accomplishment of a project.

in carrying out the scheduled program.[1]

Costs are never completely disregarded in project scheduling. Although a national emergency might temporarily suspend economic considerations, the occurrence of an industrial organization pursuing a "speed at any price" criterion is rare. Therefore, the cost parameter should be examined through a cost analysis of any project schedule. A cost analysis is prepared in order to arrive at the most practical and economical schedule that will still adhere to a project's time constraints. Total project cost includes more than a summation of activity or task costs comprising the project. There may also be time constraints in addition to task time constraints. Therefore, factors outside the project, as well as those within, must be included in the analysis of the cost parameter.[2]

From the initial estimates for activity times, the total project duration can be determined. If this project duration is too long due to contractual or technological reasons, then time must be compressed or shortened in some optimal time versus cost manner. This problem is resolved by buying or selling time along the critical path of the

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[1] Joseph J. Moder and Cecil R. Phillips, Project Management with CPM and PERT (New York: Reinhold Publishing Corporation, 1964), pp. 1-2.

[2] James L. Riggs and Charles O. Heath, Guide to Cost Reduction through Critical Path Scheduling (Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1966), pp. 103-104.

project at a minimum cost. The determination of an optimal schedule by means of time-cost trade-offs is complicated by the large number of possible time-cost combinations involved. Thus, a project manager should use all available management tools to insure that he arrives at an optimal schedule in order to minimize costs and maximize profits. In order to utilize the tools, he must know what provisions are included in these systems and how they can be applied to arrive at decisions leading to project time-cost optimization.

Purpose and Scope

The purpose of this study is to explicitly define and conduct a critical analysis of the provisions for time-cost trade-offs included in network-based scheduling systems for use in project management, and to describe how these provisions can be applied for project time-cost optimization. Some of the substantive issues that will be explored are:

1. What are network scheduling systems?

2. How is project duration related to total project cost in these systems?

3. What provisions for time-cost trade-offs are included in these systems?

4. How can these trade-off provisions be applied for project time-cost optimization decisions?

To analyze the provisions for time-cost trade-offs for project time-cost optimization, this paper is organized

to:

1. Describe the Critical Path Method and Program Evaluation and Review Technique.

2. Describe and appraise the performance of time compression on a project network schedule.

3. Effect a critical analysis of significant assumptions, benefits, and shortcomings of the time compression technique.

Method of Presentation

This report will be presented in five chapters. Chapter I is the introductory chapter which presents the purpose and direction of the paper.

Chapter II presents the historical development of the Critical Path Method network scheduling system. The basic principles of this system and the provisions for time-cost trade-offs for project time-cost optimization are reviewed and illustrated. This chapter is concluded with a summary of the advantages and disadvantages of CPM.

Chapter III traces the development of the Program Evaluation and Review Technique. Basic principles of the system as they differ from CPM are discussed and illustrated and provisions for time-cost trade-offs for time-cost optimization are ennumerated. PERT/Time and PERT/Cost concepts are presented separately. The PERT supplements, the Time-Cost Option Supplement and the Resource Allocation Supplement, are thoroughly presented because these supplements

contain the PERT provisions for time-cost trade-offs. This chapter is concluded with advantages and disadvantages of the all-inclusive PERT system.

Chapter IV presents the essentials of project time-cost optimization and how optimal project time-cost schedules can be derived from network scheduling systems. Time compression theory is discussed and a general time compression method applicable to both CPM and PERT is illustrated. Time compression assumptions, benefits and shortcomings, and time-cost curves as they pertain to project time-cost optimization are analyzed.

The final chapter, Chapter V, contains the conclusions drawn from analysis of the previous chapters. The conclusions are specifically related to the research questions.

Sources of Information

There is considerable literature devoted to PERT and CPM and all their variations, but it is largely associated with the initial concepts and experiences of the early 1960's. This paper attempts to incorporate all the latest developments of these systems. Most of the information contained in this paper has been obtained through library research; however, a number of personal interviews were conducted with prominent, knowledgeable officials in the management systems field from the National Aeronautics and Space Administration, the Center for Naval Analysis, the Navy's Special Projects

Office, and the Office of the Assistant Secretary of Defense (Comptroller). Current periodicals, pamphlets, reports, magazines and books were utilized in order to expand the objectivity of the paper.

Significance

With the successful applications of PERT in the Polaris program, and the successes of CPM in the chemical and construction industries, the use of network scheduling systems has grown at a rapid rate. In addition to their value as planning and control techniques, the systems provide a tool for planning toward optimum project time-cost relationships. They further provide a powerful new vehicle for the control of costs throughout the course of a project. Most cost accounting systems in industry are functionally oriented; that is, cost data by cost centers is provided within the company organization rather than by project.[1] By the utilization of project networks for project accounting, expenditures can be coded to apply to the tasks or groups of tasks comprising a project, thus enabling project management to monitor costs as well as scheduled progress of work.[2]

As a result, many large agencies of the U. S. Government require the use of PERT and CPM supplemental cost control

[1] Moder and Phillips, Project Management with CPM and PERT, p. 10.

[2] Ibid.

techniques in projects contracted to private organizations. The government requires the prime contractor and major subcontractors to utilize some form of network-based progress reporting for almost every major research and development program, especially weapon systems programs. With the advent of the program package concept introduced into the Department of Defense, a new awareness for project management and further developments of PERT and CPM has evolved, making it imperative that project managers keep informed.[1]

[1] Ibid., pp. 10-11.

CHAPTER II

THE CPM SCHEDULING SYSTEM

Historical Development

The first aid used by management to schedule activities was the Gantt chart. As shown in Figure 1, the basic Gantt chart portrayed activities on the ordinate against time on the abscissa.[1]

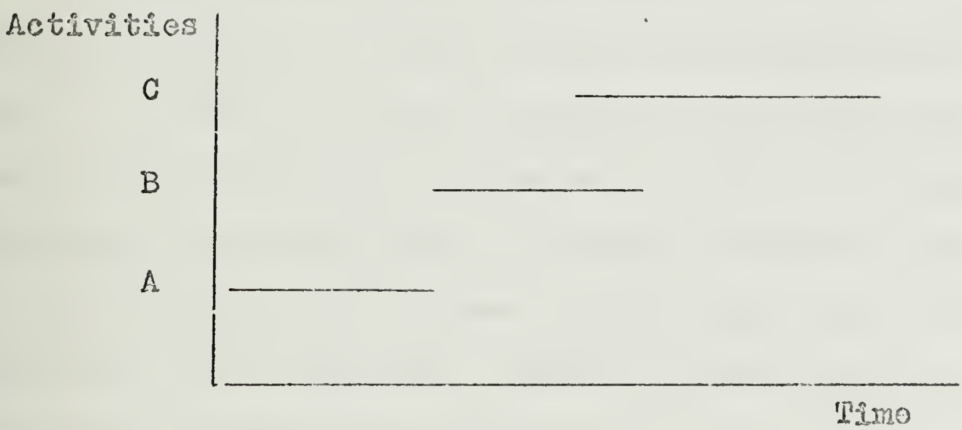

Fig. 1.--Gantt chart

This technique, or slight modification, is still frequently used in production scheduling in industries where high volume items are manufactured, where production activities

[1]Moder and Phillips, Project Management with CPM and PERT, pp. 3-4.

are similar or identical from one scheduling period to the next, and where production time per item is standard and known. Then, the activities A, B, and C on the Gantt chart might represent the manufacture of three different parts on the same production line where the sequence is determined by a tooling change. It is seen that A and B are made independently whereas B and C are made simultaneously for a period of time. Here the chart portrays that portion of time that the same tooling is used on both, thus increasing production efficiency by eliminating an extra tooling change.

Although the Gantt chart showed some relationships between activities, it did not show interdependencies explicitly.[1] So long as projects remained relatively small, and the interdependency of activities was minor, the Gantt charting technique was satisfactory. However, as the size and complexity of projects increased, it was evident that better scheduling techniques were necessary. Sparked by this necessity, the Integrated Engineering Control Group of E. I. du Pont de Nemours and Company began a study in 1956 in an effort to correct deficiencies in traditional scheduling and planning procedures. A scheduling procedure which revealed interdependencies and interrelationships was needed. From this study a network scheduling concept emerged. The group recognized that network activity time estimates were variable; however, the principle use of this concept was intended for maintenance

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[1] Ibid.

and construction projects where reliable time estimates could be obtained from past experience. The group then assumed that activity times were deterministic rather than variable. This did not place a restriction on the concept for its intended use.[1]

This original network scheduling method was called Critical Path Method (CPM), for it showed the precedence relationships in a project as a result of the interdependencies among the many tasks comprising a project.

Basic Principles of CPM

To apply the Critical Path Method, it is first necessary to break down the project under consideration into all its basic tasks or activities. An activity is defined as any task or action that must be performed which requires time and can be defined relative to time. An activity is represented by an arrow in a schedule flow chart as depicted in Figure 2.

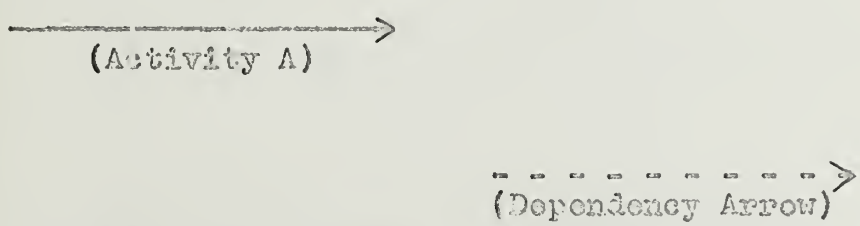

Fig. 2.--Activity and dependency arrows

Another arrow seen in the project flow chart is a dependency

[1] *Ibid.*, pp. 1-7.

arrow which shows precedence only and has a zero time value. It indicates that one activity must be initiated and completed before a succeeding activity can be initiated.[1]

An event in a project network is an instantaneous occurrence whose accomplishment must be known at an unambiguous point in time. Events represent meaningful accomplishments within the overall plan and they signify the initiation or completion of one or more activities. An event is usually called a node in a project network and is represented by a numbered circle.[2]

A project scheduling network flow chart is constructed of activities and events as shown in Figure 3.

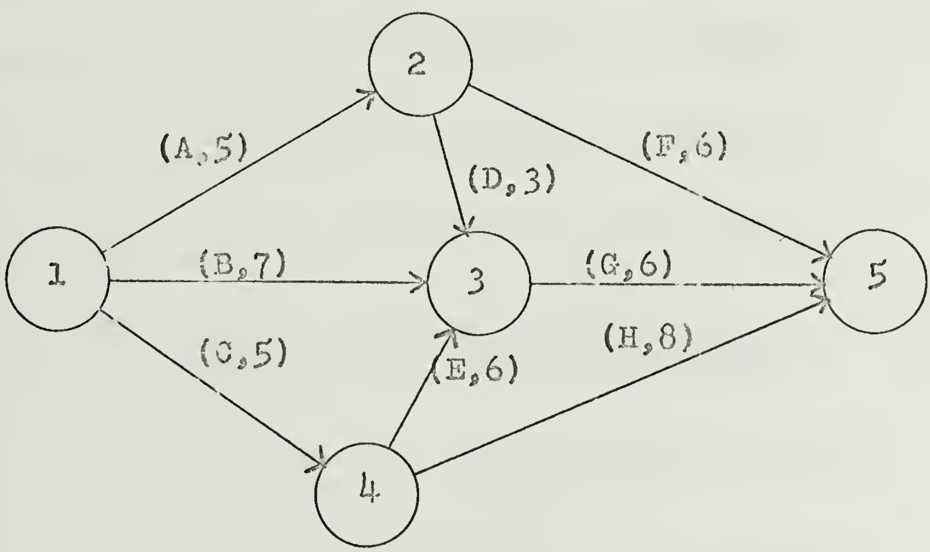

Fig. 3.--Project scheduling network

As an example of network interpretation, consider activity

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[1] Ibid., pp. 15-16. [2] Ibid.

G, the arrow to center right in Figure 3. This activity cannot begin until event 3 occurs, and event 3 will occur when activities B, D, and E are completed. This represents the precedence relationships and interdependencies for activities in this project.

For project management, the use of arrow diagramming to create a project network flow chart has the following benefits:

> 1. The diagram is a working model--it can be followed by anyone with very little explanation. Creating an arrow diagram is much more complex than reading one.
>
> 2. By means of a diagram, the entire project scope can be immediately, and visually, assimilated.
>
> 3. Problems are resolved, on paper, before they occur.
>
> 4. The chance of omission is substantially reduced.
>
> 5. Coordination of work and deliveries is achieved.
>
> 6. Work is planned in the order in which it must be done rather than in which it could be done.
>
> 7. For each job, all prerequisite work is always immediately evident.
>
> 8. Preparing an arrow diagram requires the cooperation of the people who will supervise or do the work. The result will be their plan--something they respect--rather than something imposed upon them.[1]

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[1] R. L. Martino, Project Management and Control, Vol. 1: Finding the Critical Path (New York: American Management Association, Inc., 1964), p. 48.

Since activity times are assumed deterministic in CPM, they are constant. The time length of the project is the longest continuous path time-wise through the network; this path is defined as the critical path.[1] The calculation of the critical path is illustrated in Figure 4.

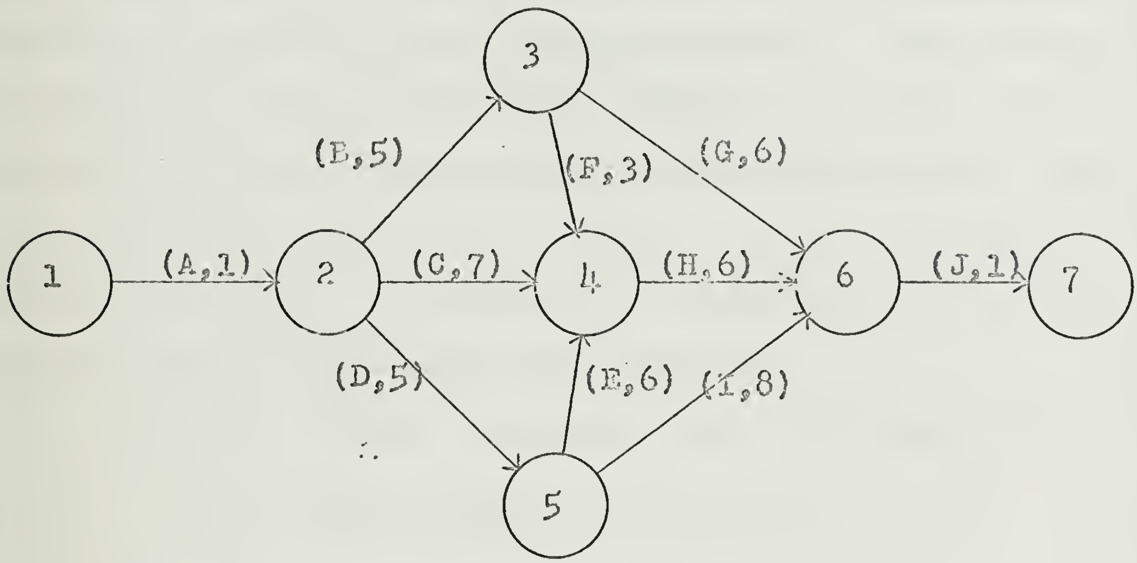

Fig. 4.--Project network

The computations begin by assigning times to the activities.[2] These times are the result of experience judgments by the manager. Because the CPM approach finds its greatest use in the construction industry and other industries of a similar nature, the manager can almost positively predict

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[1] Ibid., p. 102.

[2] Times are usually expressed in days, but fractional days or hours are sometimes employed.

the time of any given activity.[1] A high degree of accuracy is obtained from valid experience factors which result from the repetitive nature of the work. By summing activity times along the path leading to an event, an earliest occurrence time (t^e) is established for the event. The earliest occurrence time is the earliest time all related activities preceding a chosen activity can be completed.[2] Since there is frequently more than one path leading to an event, it is necessary to choose the greatest sum of activity times (the longest path) to establish the correct earliest occurrence time for the event. An event is not complete until all activities leading to it have been completed.

Let t_1^e = earliest occurrence time for event 1

y_A = time duration for activity A

then,

$t_1^e = 0$ (no activity constraints on event 1)

which gives

$$t_2^e = t_1^e + y_A = 1$$

$$t_3^e = t_2^e + y_B = 1 + 5 = 6$$

At event 4 the situation is somewhat different as

$$t_4^e = \max(t_3^e + y_F;\ t_2^e + y_C;\ t_5^e + y_E)$$

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[1] David M. Stires and Maurice M. Murphy, PERT/CPM (Boston, Mass.: Farnsworth Publishing, Inc., 1962), pp. 119-120.

[2] Riggs and Heath, Guide to Cost Reduction Through Critical Path Scheduling, p. 60.

All earliest occurrence times are shown in Table 1.

TABLE 1

CRITICAL PATH CALCULATIONS

Path	Activity Times	T_E
1-2-3-6-7	1+5+6+1	13
1-2-3-4-6-7	1+5+3+6+1	16
1-2-5-4-6-7	1+5+6+6+1	19
1-2-5-6-7	1+5+8+1	15
1-2-4-6-7	1+7+6+1	15

There are five paths leading to event 7; thus, the longest path from event 1 to event 7 is selected to obtain the cumulative earliest occurrence time (T_E) for event 7. The resultant longest path is the critical path because it establishes the greatest time constraint on the completion of the end event. Any activity on the critical path that requires time in excess of the original time, will cause completion of the end event to be delayed correspondingly. In the example, 1-2-5-4-6-7 is the critical path, requiring 19 units of time.

A corollary to the t^e calculation is the t^1, latest occurrence time. This is the latest date on which an event can occur without delaying the completion of the end event.[1] Calculations are begun by moving all activities forward in time as far as possible without increasing the length of the

[1] Ibid.

project; then, the latest occurrence time for each event is calculated. The T_L, project latest occurrence time, for the end event is established by the critical path time value. Starting with the end event, subtract the activity time of each activity constraining the event from the T_L of the end event. This will establish the t^1 for each event which is an immediate constraint on the end event. The calculations for Figure 4 are as follows:

Let t_1^1 = the latest occurrence time for event 1,

then

$$t_7^1 = T_L = 19$$

and this gives

$$t_6^1 = t_7^1 - y_J = 19-1 = 18$$

$$t_4^1 = t_6^1 - y_H = 18-6 = 12$$

At events 3 and 5, a different situation arises, since

$$t_3^1 = \min(t_6^1 - y_G;\ t_4^1 - y_F)$$

and

$$t_5^1 = \min(t_6^1 - y_I;\ t_4^1 - y_E)$$

In this case, $t_3^1 = 9$, and $t_5^1 = 6$. The remaining calculations are similar. In order to illustrate this calculation in a convenient manner in the network, the node event representation is frequently done as in Figure 5.

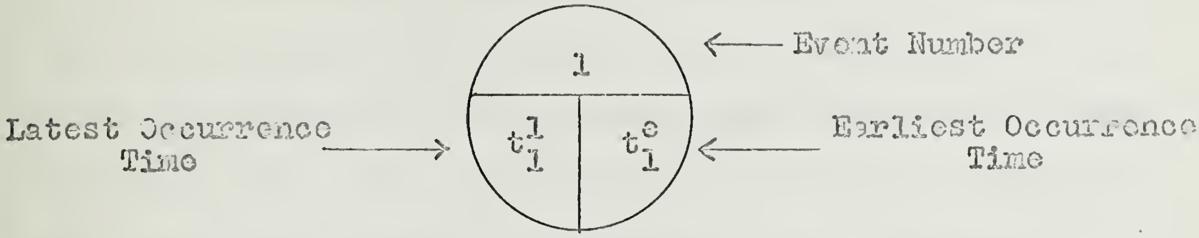

Fig. 5.--Event designation

All calculations for the above example are shown in Figure 6.

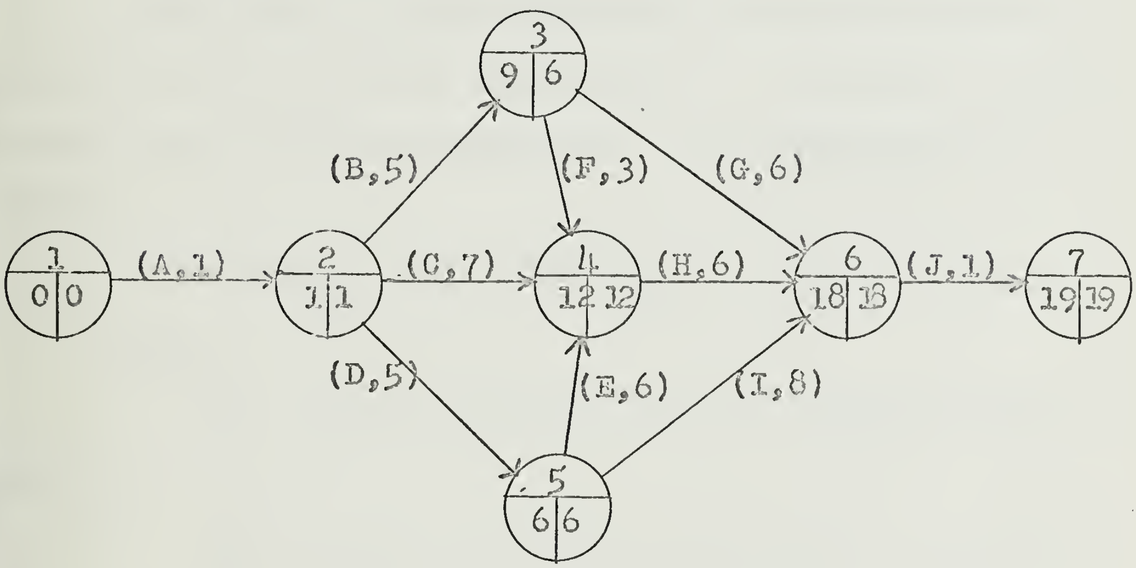

Fig. 6.--Earliest and latest occurrence times calculations

The maximum time available for any activity (a) is $t_a^l - t_a^e$ for that activity; if this time exceeds the determined activity time, the activity is said to have slack time or float.[1] For all activities on the critical path, the quantity

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[1]L. R. Shaffer, J. B. Ritter, and W. L. Meyer, The Critical-Path Method (New York: McGraw-Hill, Inc., 1965), pp. 32-33.

$t_a^l - t_a^e$ will be zero. Slack will be present in a network flow diagram when there are two or more combinations of activity paths when proceeding from the starting event to the objective event. The amount of slack that each event contains is closely analyzed by management and indicates the degree of flexibility that is present in the program schedule.

The three types of slack that the Critical Path Method computes are total slack, free slack, and independent slack.[1]

Total slack is the difference in time between the latest occurrence time an activity may be completed and the earliest time it can be completed.[2] It is defined by the formula:

$$\text{Total Slack} = t_a^l - (t_p^e + t_a)$$

where

t_a^l = latest occurrence time for the successor event

t_p^e = earliest occurrence time for the predecessor event and

t_a = activity time for activity a.

Total slack indicates the time an activity can be delayed without changing the project duration.

Free slack is that amount of slack found if all

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[1]Stires and Murphy, PERT/CPM, p. 157.

[2]Ibid.

activities in a project are started as early as possible. It is that amount of time by which an activity start time can be delayed without affecting slack for successive activities.[1] Then,

$$\text{Free slack} = t_s^e - (t_p^e + t_a).$$

Independent slack is the amount of slack that is irreducible in a path of activities. Independent slack exists when a predecessor event can occur at its latest occurrence time (t^l) and still allow succeeding activities to be accomplished before a successor event's earliest occurrence time (t^e).[2]

$$\text{Independent slack} = \text{Max}\ (0;\ t_s^e - (t_p^l + t_a))$$

Figure 7 illustrates the computation of slack.[3] Note the starred values in the independent slack column are actually negative but are expressed as zero.

These slack calculations are used to analyze the network and frequently serve as a basis for adjustment of resources in an effort to shorten the critical path. If a project deadline is imposed, the latest occurrence time for the last event in the network can be set equal to this deadline. If the deadline is less than the earliest occurrence time of the last event, some slack calculations will be negative indicating that activity times must be shortened to meet the imposed deadline.

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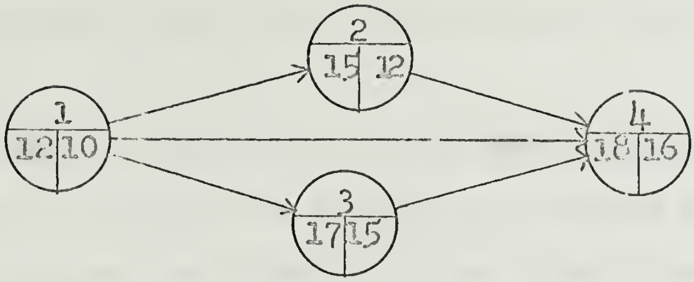
[1] Ibid.

[2] Ibid., p. 158.

[3] Ibid., p. 159.



Activity		Slack		
Pred.	Succ.	Total	Free	Independent
1	2	3	0	0*
1	3	2	0	0*
1	4	5	3	1
2	4	3	1	0*
3	4	2	0	0*

Fig. 7.--Slack computations

Using CPM, each activity in the network receives two time estimates: "normal" time, and "crash" time. Normal time estimate is the minimum time associated with completing the job at minimum cost. Emphasis is on minimum cost. Crash time estimate is the time for accomplishing the job in the absolute minimum time with the minimum cost necessary to achieve that time. Emphasis is on minimum time.[1]

Based upon these two estimates for each activity, alternate plans are developed. Alternatives range from "normal" effort on all activities to "crash" effort on all critical path activities. Various combinations lie in between

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[1] Ibid., pp. 120-121.

these two extremes where only selected activities are "crashed."

Time has a monetary value or cost. Thus, if the time required to complete a project is reduced by adding additional manpower or resources, the direct cost of the project increases. By plotting the various time estimates with their corresponding effects upon direct costs, a time-cost curve similar to Figure 8 results.[1] It is important

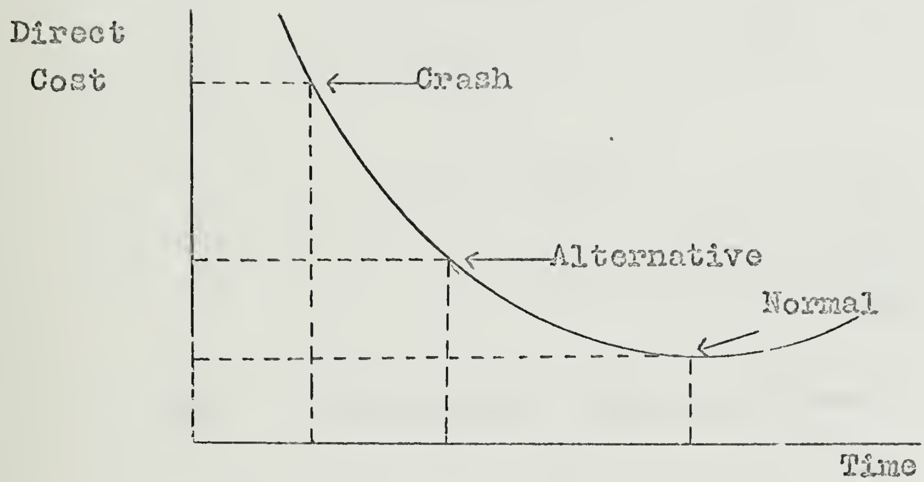

Fig. 8.--CPM activity time-cost curve

to note that placing "crash" effort on all activities is not a relevant alternative, for this maximizes costs. There is nothing to be gained by putting "crash" effort on a non-critical activity.

If there is a specified time set for project completion, the planner knows his maximum time limit. If no time is specified, the planner uses the "normal" time estimate.

[1] Ibid., pp. 122-123.

To minimize costs and increase efficiency the planner combines his project direct cost curve with project indirect costs. By combining all costs into a total cost curve as seen in Figure 9, the planner can identify the time associated with the minimum total project investment cost.[1]

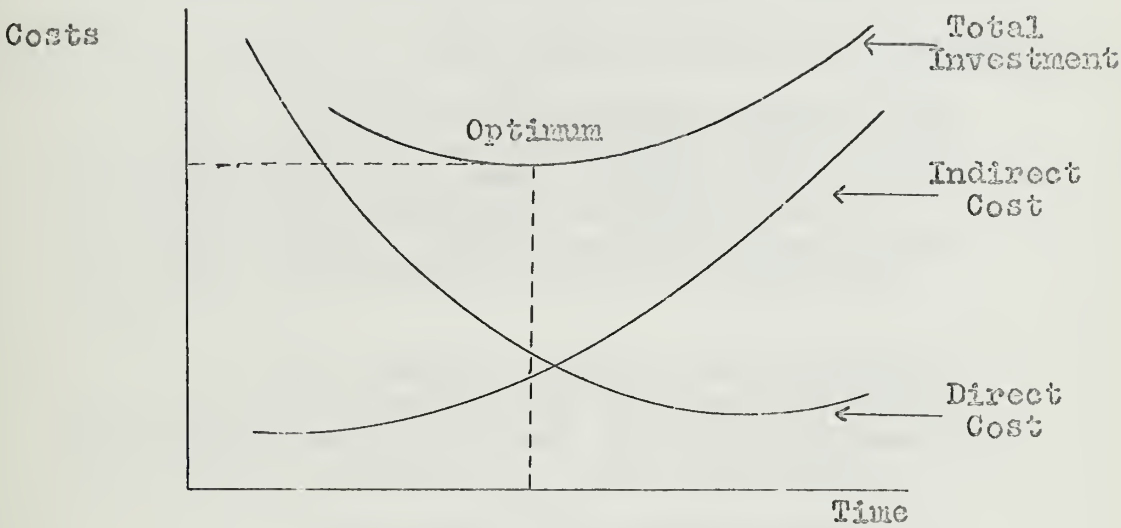

Fig. 9.--CPM project time-cost curves

Advantages and Disadvantages

With twelve years experience using CPM, management has found that CPM provides the following advantages:

1. CPM enforces a discipline in planning and scheduling which is not accomplished as well with the traditional methods.

2. CPM does allow management to manage-by-exception.

3. CPM allows for an improvement in communication and coordination among the several departments in the firm.

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[1] *Ibid.*, pp. 124-126.

4. CPM can make planners and schedulers more competent.

5. CPM allows for an improvement in communications and coordination among the several organizations required for completing the work.

6. CPM provides management with a tool to measure the ability of planners.[1]

In addition to the above advantages, the critical path technique offers the following corollary advantages:

1. It provides the project manager with specific information that permits him to set an objective and rigorous schedule and to discuss with his management or client, on a practical basis, why that schedule was chosen and what considerations will be involved in changing it.

2. With dynamic reporting and updating the technique provides top management with an integrated summary picture of total progress and progress outlook on a continuous basis.

3. It simplifies the communications problem through a detailed action plan using a common language for all groups. The preparation of the plan requires job responsibilities to be clearly pinpointed. Failure to meet schedule times can be checked periodically against the original plan and the true cause for failing to meet completion dates can be clearly stated.

4. CPM tightens up work performance and reveals inadequacies in methods, individual skills, supervisory direction, and manpower balance. Many times, improvements in control practices and supervision are necessary.

5. It places a dollar value on change. Thus able to relate time schedules to cost, management can readily justify methods improvement. Most important, methods work can

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[1]Shaffer, Ritter, and Meyer, <u>The Critical Path Method</u>, pp. 165-186.

> be directed to those portions of a project or shutdown where the greatest gain for the least expenditure of dollars and technical effort can be achieved.[1]

The disadvantage associated with CPM is the feeling that CPM is a cure-all. It is imperative that management understand that CPM is not a panacea. It cannot be used as a substitute for the knowledge and understanding which the project manager has gained from practical experience. CPM is only an information-generating process which can aid the project manager in the planning, scheduling, and controlling of a project.[2]

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[1]Gabriel N. Stilian and Others, PERT: A New Management Planning and Control Technique (New York: American Management Associates, 1962), pp. 162-163.

[2]Shaffer, Ritter, and Meyer, The Critical Path Method, p. 184.

CHAPTER III

THE PERT SCHEDULING SYSTEM

Background

The Program Evaluation Branch of the Special Projects Office of the Navy was confronted with many problems in scheduling the Polaris Fleet Ballistic Missile program. This program involved research, development, fabrication, testing, producting, and staffing of a continental ballistic missile system. The Special Projects Office started scheduling this project by the existing technique which was a basic application of the Gantt chart with time deadlines specified. Due to the thousands of activities and the high degree of dependency, it became apparent that a new technique was needed. Consequently, in early 1958, the consulting firm of Booz, Allen, and Hamilton, working in conjunction with the Special Projects Office of the U. S. Navy, was given the task of advancing a suitable scheduling procedure. This work was carried out independently of the work being performed by du Pont on CPM.

The Polaris program involved considerable research and development; therefore, activity times were extremely variable and were so regarded in the final technique. As in

CPM, the scheduling technique used a network to show precedence relationships. This scheduling technique was named PERT for Program Evaluation and Review Technique.

PERT is a recent addition to the project manager's store of information tools. It is primarily a tool of evaluation which deals with three of the most important management elements in the operation of an effective project: first, it appraises the validity of plans and schedules for carrying out the project; second, it measures the progress achieved; third, it measures the outlook for meeting the project's objectives.[1]

The three foregoing elements are monitored continuously during the operation of the project. This provides the manager with current status information. PERT is designed for any project or program which is a non-repetitive performance or work task to achieve an objective goal.[2] It is applicable to almost any endeavor which requires a systematic or planned approach to reach a desired objective. The impression that PERT and its derivatives are useful only in large, one-time development programs should be dispelled. The approach has been utilized in the following areas:[3]

1. The installation of a new computer.

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[1]Stiers and Murphy, PERT/CPM, p. 3.

[2]David M. Stires and Raymond P. Wenig, PERT/COST (Boston: Farnsworth Publishing, Inc., 1964), p. 6.

[3]Stilian and Others, PERT, p. 26.

2. The shelter program in civil defense.
3. The new-product process.
4. Construction and maintenance activities.
5. The financial forecasting process.
6. Mining operations.
7. Real estate development programs.
8. Highway construction.
9. Cost control.
10. Documentation Control.
11. Valve engineering.

Basic Principles

PERT is a management planning and control technique which, as in CPM, utilizes a network to depict the essential relationships between the various tasks comprising a project. It is a set of principles, methods, and techniques for effective planning of objective-oriented work thereby establishing a sound basis for effective scheduling, costing, controlling, and replanning in the management of programs or projects.[1] PERT is generally categorized into two systems, PERT/Time and PERT/Cost. The original PERT concept developed by Booz, Allen, and Hamilton did not include the function of recording and controlling costs; this was added later to PERT/Time and was called PERT/Cost. PERT/Time will be covered

[1]U. S., Department of the Navy, Special Projects Office, SP PERT Handbook (Washington, D. C.: Special Projects Office, 1965), p. I.6.

first, then PERT/Cost.

PERT/Time

Five elements of PERT/Time, essential for its employment are:

> 1. A product oriented work breakdown structure, beginning with these objectives subdivided into successively smaller end-items.
>
> 2. A flow plan (network) consisting of all the activities and events that must be completed or accomplished to reach the program objectives, showing their planned sequence of accomplishment, interdependencies, and interrelationships.
>
> 3. Elapsed time estimates and identification of critical paths in the networks.
>
> 4. A schedule which attempts to balance the objectives, the network flow plan, and resources availability.
>
> 5. Analysis of the interrelated networks, schedules and slack values as a basis for continuous evaluation of program status, forecast of overruns, and the identification of problem areas in time for management to take corrective action.[1]

The PERT system employs the above elements by first listing all significant progress milestones which are to be achieved throughout the life of the program. These milestones are arrayed, sequentially, and connected to each other by appropriate activities required to advance through the network as in CPM. A PERT milestone, commonly referred to

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[1] U. S. Office of the Secretary of Defense, PERT Coordinating Group, PERT Guide for Management Use (Washington, D. C.: Government Printing Office, 1963), p. 3.

as a PERT event, is a finite accomplishment necessary to obtain a given objective and worded in such a way that at any point in time there can be no question of what it is or what has to be done. For a PERT network to operate it is essential that an end objective or end event be clearly defined.

Once all events and activities are defined and the end objective is stated, time estimates are made for each activity. Here, PERT differs from CPM. In PERT, activity times are assumed to be variable and hence must be estimated. The procedure is to obtain three time estimates from competent project personnel for each activity. The three time estimates are commonly called the <u>optimistic</u>, <u>pessimistic</u>, and <u>most likely</u> times for an activity. The estimates are defined as follows:

> <u>Optimistic time (a)</u> -- the time required to complete the activity under the best conditions. This time is unlikely to be achieved but is possible if everything goes exceptionally well. It is estimated that an activity would have no more than one chance in a hundred of being completed within this time.
>
> <u>Most likely time (m)</u> -- the most realistic estimate or most probable activity time. This time would be expected to occur most often if the activity could be repeated

numerous times under similar circumstances.

Pessimistic time (b) --- the longest time an activity would require under the most adverse conditions, barring acts of God. This estimate also represents the worst case of one in a hundred.[1]

By requiring three time estimates, it was thought the estimator would become disassociated from his built-in knowledge of the existing schedule and provide more reliable information about the inherent difficulties and variability in the activity being estimated. The three time estimates are combined mathematically by two formulas which yield the PERT activity expected time (t_s^m) and the variance (σ_s^2). The expected time is the time that divides the total range of probability in half.[2] There is a 50-50 chance that the time actually required will be equal to or greater than the expected time. The expected time or mean time is given by

$$t_s^m = \frac{a + 4m + b}{6}; \text{ for activity s.}^3$$

The variance of the expected time is a measure of its degree of uncertainty. This measure reveals the width or spread of the center 50 per cent of the total distribution so that there is a 50 per cent probability that the activity will occur within the expected time--plus or minus so many units

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[1]PERT Coordinating Group, PERT Guide, p. D. 3.

[2]Stilian and Others, PERT, p. 62.

[3]Ibid., pp. 110-111.

of time.[1] The variance is given by

$$\sigma_s^2 = \left(\frac{b-a}{6}\right)^2 \text{ for activity } s,^2$$

and standard deviation by

$$\sigma_s = \frac{b-a}{6} \text{ for activity } s.$$

The critical path is found by using t_s^m for each activity and proceeding as in the CPM scheduling technique.

To illustrate, consider the project network in Figure 10, with time estimates for each activity designated by (a, m, b).

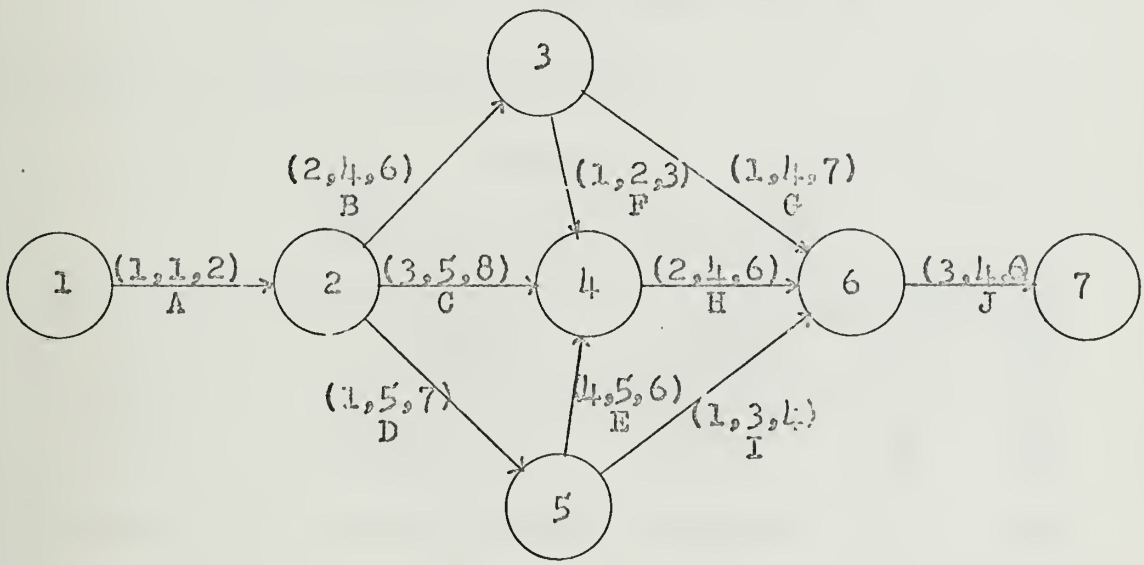

Fig. 10.--PERT project network

From this, the following expected activity times and standard deviations can be obtained:

$$t_A^m = \frac{1 + 4 + 2}{6} = \frac{7}{6}; \quad \sigma_A = \frac{2-1}{6} = \frac{1}{6}$$

$$t_B^m = \frac{2 + 16 + 6}{6} = \frac{24}{6}; \quad \sigma_B = \frac{6-2}{6} = \frac{4}{6}$$

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[1] Ibid., p. 62.

[2] Ibid., p. 111.

$$t_C^m = \frac{3 + 20 + 8}{6} = \frac{31}{6}; \quad \sigma_C = \frac{8-3}{6} = \frac{5}{6}$$

$$t_D^m = \frac{1 + 20 + 7}{6} = \frac{28}{6}; \quad \sigma_D = \frac{7-1}{6} = \frac{6}{6}$$

$$t_E^m = \frac{4 + 20 + 6}{6} = \frac{30}{6}; \quad \sigma_E = \frac{6-4}{6} = \frac{2}{6}$$

$$t_F^m = \frac{1 + 8 + 3}{6} = \frac{12}{6}; \quad \sigma_F = \frac{3-1}{6} = \frac{2}{6}$$

$$t_G^m = \frac{1 + 16 + 7}{6} = \frac{24}{6}; \quad \sigma_G = \frac{7-1}{6} = \frac{6}{6}$$

$$t_H^m = \frac{2 + 16 + 6}{6} = \frac{24}{6}; \quad \sigma_H = \frac{6-2}{6} = \frac{4}{6}$$

$$t_I^m = \frac{1 + 12 + 4}{6} = \frac{17}{6}; \quad \sigma_I = \frac{4-1}{6} = \frac{3}{6}$$

$$t_J^m = \frac{3 + 16 + 6}{6} = \frac{25}{6}; \quad \sigma_J = \frac{6-3}{6} = \frac{3}{6}$$

The critical path is found in Table 2.

TABLE 2

CRITICAL PATH CALCULATIONS

Path	Activity Times	Std. Deviation	T_E	σ_{T_E}
1-2-3-6-7	$\frac{7+24+24+25}{6}$	$\frac{1+4+6+3}{6}$	$\frac{80}{6}$	$\frac{14}{6}$
1-2-3-4-6-7	$\frac{7+24+12+24+25}{6}$	$\frac{1+4+2+4+3}{6}$	$\frac{92}{6}$	$\frac{14}{6}$
1-2-4-6-7	$\frac{7+31+24+25}{6}$	$\frac{1+5+4+3}{6}$	$\frac{87}{6}$	$\frac{13}{6}$
1-2-5-4-6-7	$\frac{7+28+30+24+25}{6}$	$\frac{1+6+2+4+3}{6}$	$\frac{114}{6}$	$\frac{16}{6}$
1-2-5-6-7	$\frac{7+28+17+25}{6}$	$\frac{1+6+3+3}{6}$	$\frac{77}{6}$	$\frac{13}{6}$

The critical path is found to be 1-2-5-4-6-7. The expected project completion time is the sum of the expected activity

times on the longest path (the critical path), and the standard deviation is the sum of the activity standard deviations.[1] In the illustration, the expected completion time is $\frac{114}{6}$ units of time with a standard deviation of $\frac{16}{6}$ units of time.

Once the expected completion time and standard deviation are found, the probability of completing the project in that time must be ascertained. This aspect of PERT has been most controversial since its inception in the original PERT technique. The statistical argument for this calculation is based on the use of the Central Limit Theorem when there are a large number of activities (more than ten) on the critical path and their individual distributions are random. The use of the Central Limit Theorem is based upon the assumption that the distribution of possible completion times around T_E (expected completion time) for the objective event approximates the normal, or bell-shaped, distribution as seen in Figure 11.[2] This approach allows planners or schedulers to attach a probability figure to the final project completion time, although it may well be in great error according to the findings of MacCrimmon and Ryavec of the RAND Corporation. An analysis of the pros and cons of the PERT assumptions

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[1]Robert W. Miller, Schedule, Cost, and Profit Control with PERT (New York: McGraw-Hill Book Company, 1963), pp. 45-50.

[2]Ibid., p. 54.

[3]K. R. MacCrimmon and C. A. Ryavec, An Analytical Study of the PERT Assumptions (Santa Monica, Calif.: The RAND Corporation, 1962).

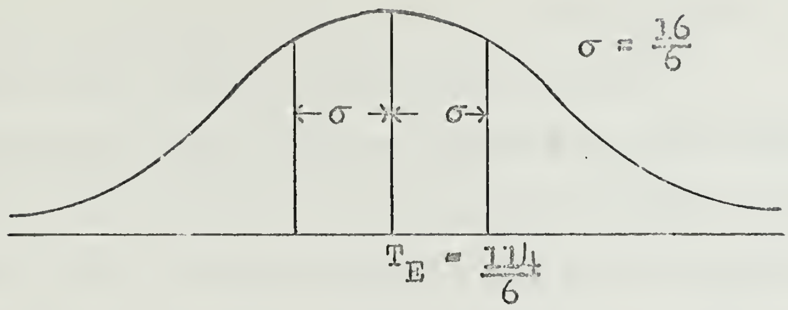

Fig. 11.--Project expected completion time distribution

will not be covered in this paper. If the beta cost distribution is not assumed and used, then the formula for the appropriate distribution should be used in place of those previously explained.

After activity time estimates are made and activity expected times are computed, the earliest occurrence times (t^e) and the latest occurrence times (t^l) are determined in the same manner, as in CPM. Once these values are derived for each event, slack time can be calculated.

In PERT, there are two categories of slack: event slack and activity slack. Event slack is the difference between the latest occurrence event time and the earliest occurrence event time (t^l-t^e). Many events have a zero slack condition; that is, the latest time and earliest time are equal. If a line were drawn through the network flow diagram connecting all zero slack events, it would form a path from the starting event to the objective event. This is the critical path, and, for all activities on this path, the quantity t^l-t^e will be zero. Events that do not lie on the critical

path are called "slack events," and activity lines connecting these events form paths called "slack paths."[1]

Activity slack differs from event slack when there is more than one activity immediately preceding an event. This is the same as total slack in CPM and is computed in the same manner using the same formula:

$$s_a = t_s^l - (t_p^e + t_a) \text{ for activity a.}$$

Slack path analysis is extremely important for effective management control for it provides the guidelines for reallocation of resources and supplies the decision-making facts necessary for fast management action.[2]

PERT/Cost

The PERT/Cost system, developed as an extension of the basic PERT/Time system, is a management tool encompassing a set of techniques for the planning and control of cost in terms of project tasks and schedules.[3] In addition to overall cost reduction, the two basic objectives of PERT/Cost are to achieve more realistic original program cost estimates and to achieve improved control against the original estimates.[4] The system correlates cost to work by requiring cost estimates

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[1]Stires and Murphy, PERT/CPM, pp. 39-40.

[2]Ibid., pp. 40-43.

[3]Anthony L. Iannone, Management Program Planning and Control with PERT, MOST, and LOB (Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1967), p. 68.

[4]Miller, Schedule, Cost, and Profit Control with PERT, p. 90.

budgets to be made for discrete tasks with identifiable beginning and ending points. It relates cost to time through the scheduling of beginnings and endings of tasks.

PERT/Cost was developed to meet the following planning and control needs of management:

1. Define the work to be performed.

2. Develop more realistic schedule and cost estimates based on the resources planned to perform the work.

3. Determine where resources should be applied to best achieve the time, cost and technical performance objectives.

4. Identify those areas developing potential delays or cost overruns, in time to permit corrective action.[1]

It was developed to enable managers at each level to determine:

1. Whether the current estimated time and cost for completing the entire project are realistic.

2. Whether the project is meeting the committed schedule and cost estimate and, if not, the extent of any difference.

3. Whether requirements for manpower and other resources have been planned realistically to minimize premium costs and idle time.

4. How manpower and other resources can be shifted to expedite critical activities.

5. How manpower and other resources can be shifted to expedite critical activities.

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[1]U. S., Office of the Secretary of Defense and National Aeronautics and Space Administration, DOD and NASA Guide: PERT COST Systems Design (Washington, D. C.: Government Printing Office, 1962), p. 1.

> 5. How manpower and other resources made available by changes in the project tasks can be best utilized.[1]

PERT/Cost requires that the PERT/Time network be fully developed before costing can be completed and that persons doing the costing have an intimate knowledge of the network. In addition, it is doubtful that an organization can implement PERT/Cost unless it has had the experience of implementing PERT/Time. These requirements are consistent with the definition and control idea of PERT/Cost, that is, the direct association of project costs with activities on an established time network.[2]

The six basic elements of the PERT/Cost system are: an orderly Work Breakdown Structure; a listing of work packages; PERT networks to relate specific work packages and the events and activities contained in them; a reporting system for estimating and recording costs by account codes which identify work packages; periodic updating of cost and time estimates to predict overruns and underruns; successive summarization of cost from work package level up through subsystems and systems to total project cost.[3] The basic tools in the system are the network and the Work Breakdown Structure

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[1] *Ibid.*, pp. 1-2.

[2] Miller, *Schedule, Cost and Profit Control with PERT*, pp. 89-91.

[3] *Ibid.*, pp. 96-122.

(WBS). The network is used primarily for planning and controlling schedules, and the WBS for planning and controlling costs. The WBS serves as the basis for construction of the PERT/Time network of project activities and events. This technique provides:

> 1. Identification and definition of all elements of work which involve the expenditure of time and dollar resources.
>
> 2. Establishment of reasonable and attainable time and cost targets, both intermediate and terminal.
>
> 3. Identification of critical problem areas during project planning and throughout project execution.[1]

The project begins with the development of the WBS (Figure 12).

After a project has been broken down into end item subdivisions, each lowest level end item subdivision is further reduced into tasks required for its accomplishment. These tasks are work packages (Figure 13) and are scheduled out as a unit. Detailed networks are constructed for each end item subdivision of the project, and network activities are identified with the work packages they represent. Once networks have been established, a time schedule is established based on the final network. According to this schedule, cost estimates and budgets are established.[2] Cost estimates are made for each work package. Estimates are based on all

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[1] Iannone, Management Program Planning, p. 67.

[2] Stires and Wenig, PERT/COST, pp. 13-14.

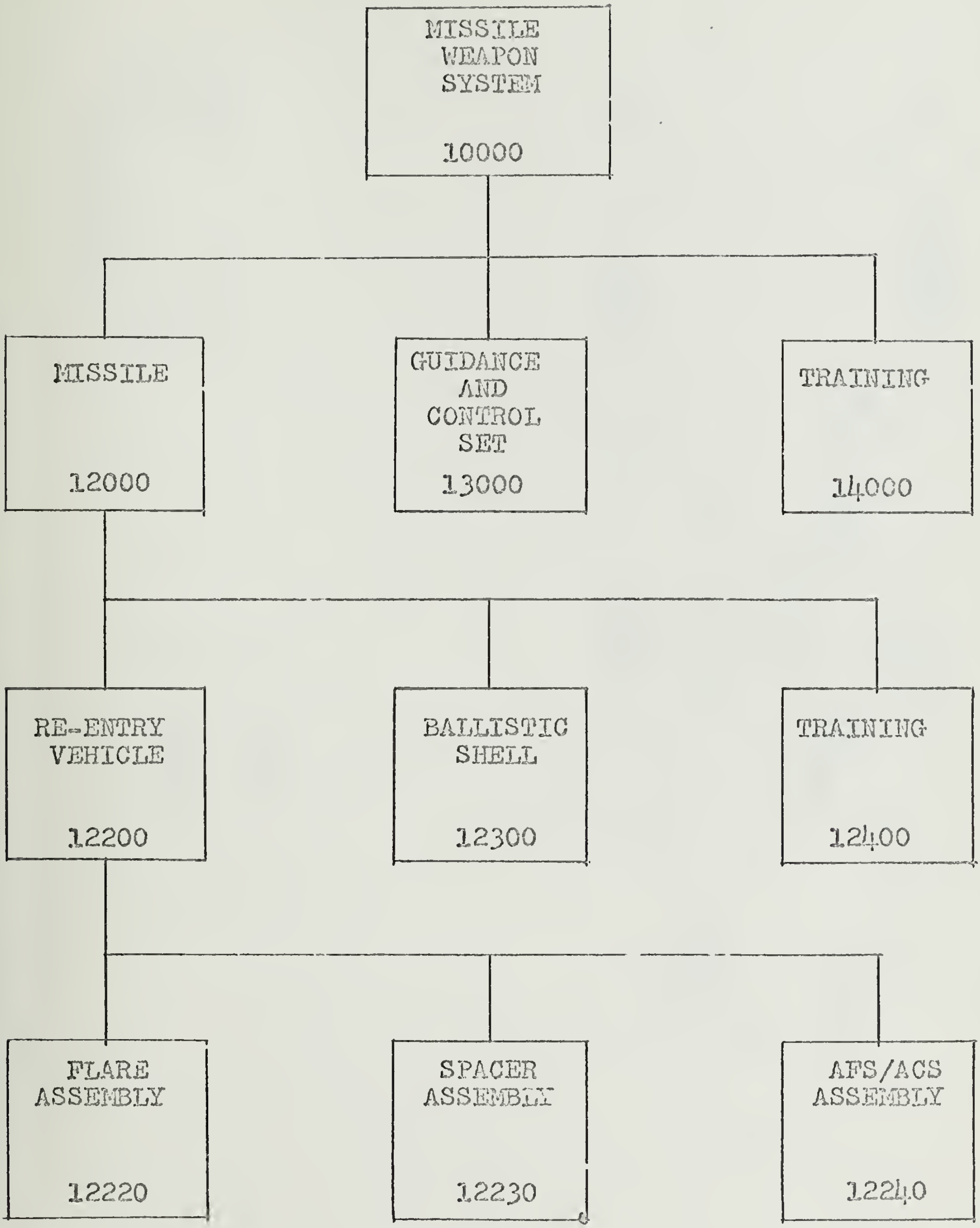

Fig. 12.--Work breakdown structure

Source: Iannone, *Management Program Planning and Control with PERT, MOST, and LOB*, p. 69.

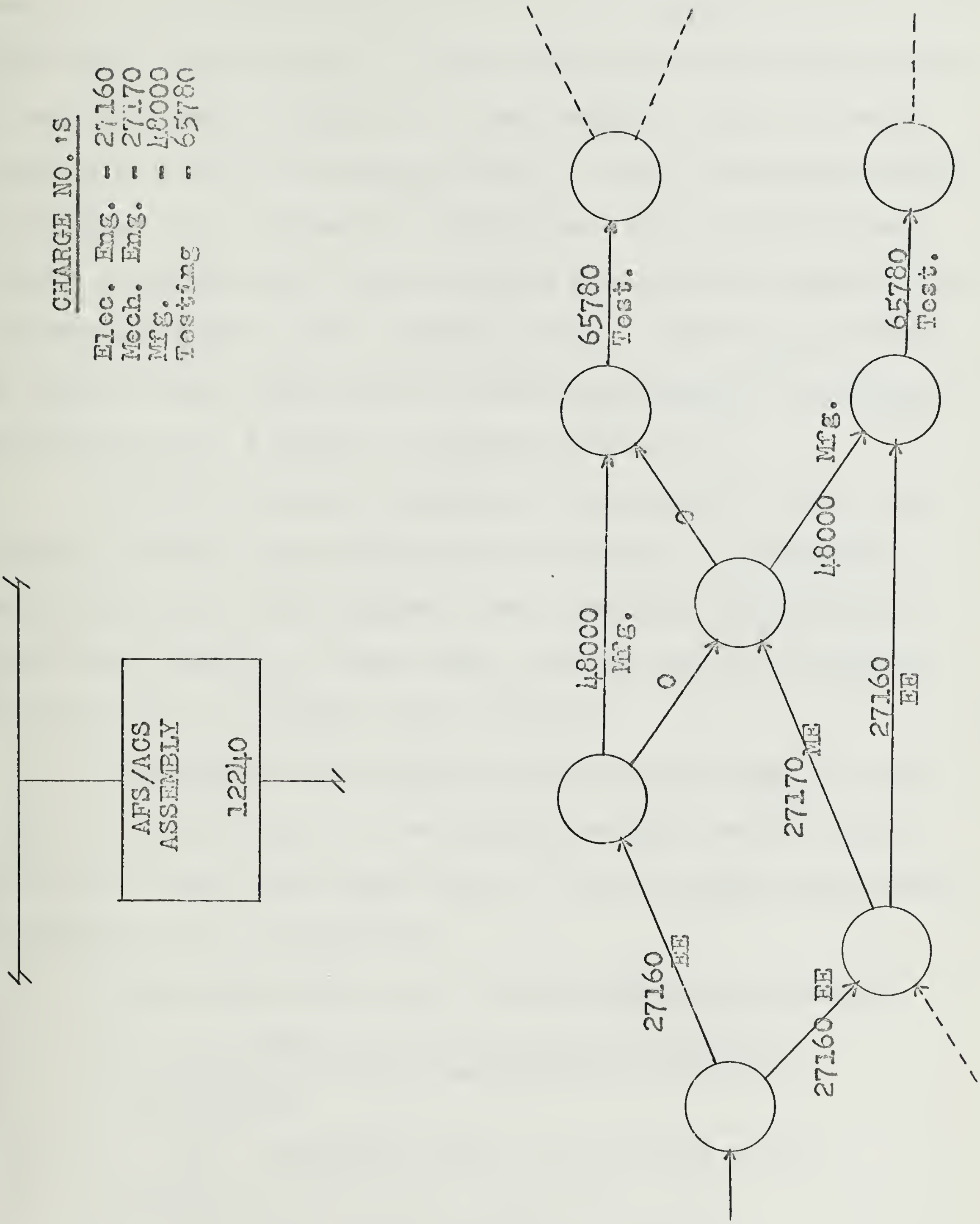

Fig. 13.--Work package

Source: Iannone, Management Program Planning and Control with PERT, MOST, and LOB, p. 70.

resources required to complete each work package in its scheduled time. By summation of cost estimates from work packages to end item subdivisions, to total project, the cost estimates are arrived at automatically.[1] Thus, the work package integrates time and cost. During the life of the project, actual times and costs are recorded and compared against the estimated figures of the original plan. Necessary revisions to the plan are made based on these comparisons, and future projections are a result of current figures.

Because the work package is handled as a unit, it affixes costing responsibility to a manager. Although it does not prevent the manager from covering overrun on one task with underrun on some other task in his work package, it does tend to minimize this problem.

To analyze the original cost estimate that was prepared for the project to see whether actual costs to date are in line with estimated costs, a cost-of-work graph shown in Figure 14 is constructed.[1]

This graph represents the following information:

1. Budgeted costs (planned costs): the amount of money required to accomplish the program.

2. Committed costs: the actual costs that are committed or expended to date.

3. Cost performance and progress: the estimate for the work performed and the progress to date based on original estimates.

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[1] SP PERT COST, p. IX. 16.

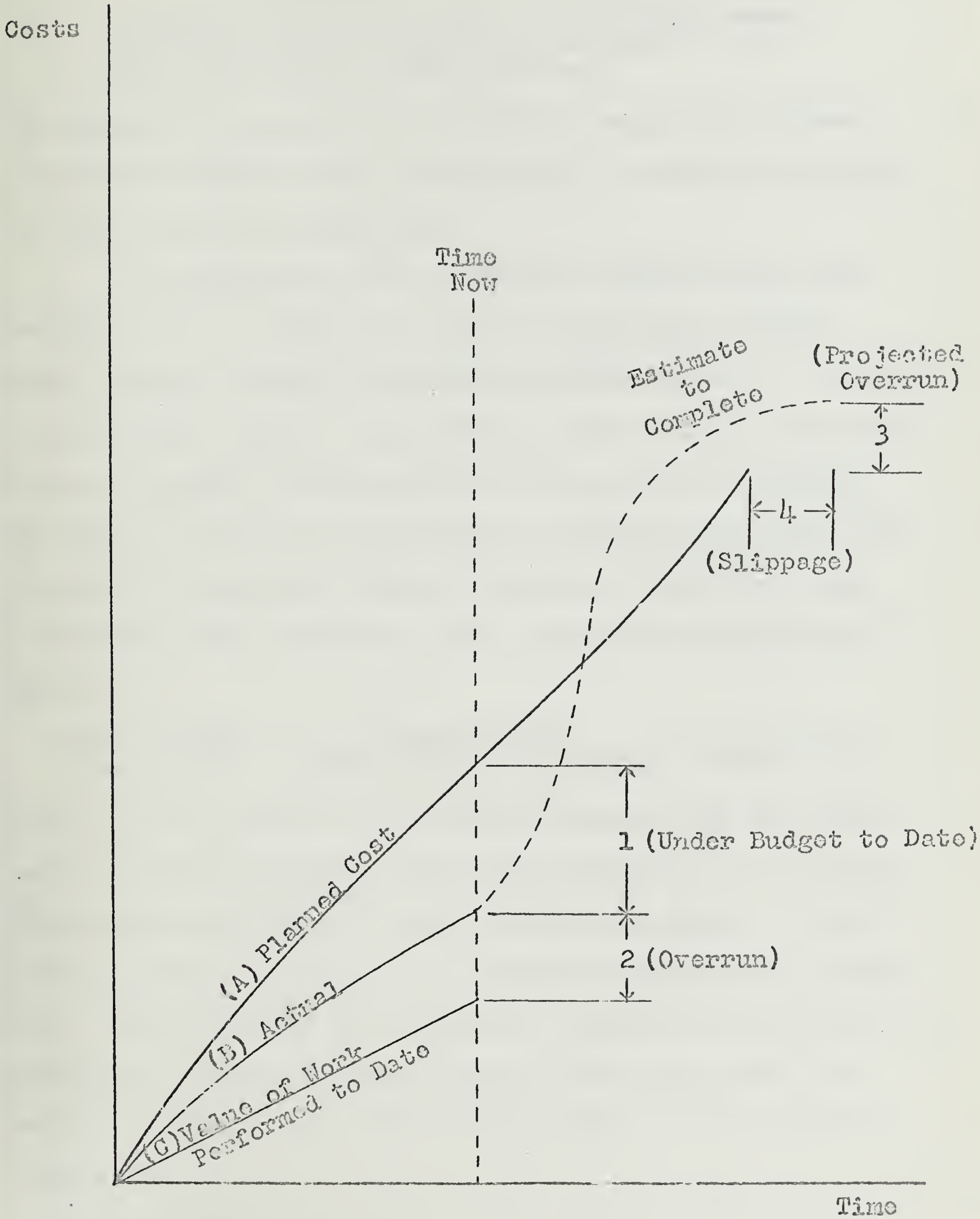

Fig. 14.--Cost-of-work report

> 4. Projected costs to complete: the estimated cost to complete the program based on actual costs to date and estimated costs for the balance of the program.[1]

This graphic representation provides a comparison between actual and budgeted costs and presents a continual forecast of cost to project completion.

In addition to the comparison between actual and budgeted costs, another tool aids in isolating trouble areas earlier. This is the Value of Work concept. Comparing actual versus budgeted expenditures may not give a true measure of progress, particularly if overruns are occurring. The Value of Work is calculated by dividing the actual cost to date by the latest revised estimate of total cost and multiplying this quotient by the contracted planned cost.[2] That is:

$$\text{Value of Work Performed} = \frac{\text{Actual Cost}}{\text{Latest Revised Estimate}} \text{ X Planned Cost}$$

Thus, if the revised cost estimate changes from the planned cost, the first quantity gives the percentage of completion which, when multiplied by the planned cost, gives a value of work accomplished which can be compared against the original plan. This concept, when applied to individual work packages, highlights potential trouble spots before they grow into serious problems, and allows management to better maintain cost control.

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[1] Stilian and Others, PERT, p. 88.

[2] Stires and Wenig, PERT/COST, pp. 261-268.

As the project progresses under PERT/Cost, three means can be used to minimize costs and optimize schedules:

> 1. Modifying the network logic sequence by changing the amount of concurrent work or the methods of work accomplishment.
>
> 2. Revising the planned resources for various work packages by shifting interchangeable resources from slack paths to critical paths
>
> 3. Rescheduling slack path activities to reduce additional hiring premium costs and idle resources.[1]

Using the above techniques, PERT/Cost gives management a powerful new way to better control costs throughout the duration of any project while concomitantly producing products on schedule.

PERT Supplements

PERT/Cost was designed primarily as a management planning and control system to utilize available resources and time to meet a program objective. It compares actual results with planned performance. PERT takes planning estimates and forms a sequenced plan of action with only partial regard for possible time and cost reduction. It does not indicate the optimum balance of time, cost, and risk necessary for objective accomplishment. After the project network has been resolved, cost estimates and budgets are prepared for the work packages based on expected activity times.[2] These cost estimates then become the control

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[1] Ibid., p. 175. [2] Ibid., pp. 13-14.

standards against which actual results are compared; thus, control of costs during operation is effective only to the extent that actual costs are monitored against expected costs. There is no positive control which seeks to minimize actual costs. This is an inherent weakness of the PERT/Cost system. Neither time estimating and scheduling nor cost estimating and controlling are undertaken with the specific purpose of minimizing cost and time while producing the required output.

To overcome this weakness, two supplements to PERT have been developed: the Time-Cost Option Supplement, and the Resource Allocation Supplement. The Time-Cost Option Supplement is a procedure for developing and evaluating alternate time and cost plans for performing the project. It assists the project manager in selecting the plan that represents the best feasible balance of time, cost, and technical risk in achieving the project objectives.[1] The Resource Allocation Supplement is a procedure for allocation of resources among project tasks to assure project completion at the lowest cost within the desired completion date.[2]

The Time-Cost Option is a procedure for adapting the PERT/Cost system to develop and display three alternative time-cost-risk plans for a project. These are the Most

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[1] DOD and NASA Guide: PERT COST, p. 5.

[2] Ibid.

Efficient Plan, the Directed Date Plan, and the Shortest Time Plan.[1] The Most Efficient Plan is a network plan that presents the most efficient use of presently available resources in meeting the technical requirements of a project.[2] This is the plan the contractor would choose if he had no specific budget or schedule limitations to observe. It does not consider cost or time constraints and usually results in the lowest technical risk for the contractor. Figure 15 demonstrates the most efficient plan for a project. Non-interdependent activities are placed in series to achieve efficiency and reduce technical risk but at the expense of project time duration. With activities placed in series, fewer resources go farther, thus reducing total project cost.

The Directed Date Plan is the network plan selected to meet the technical requirements of a project by a given date.[3] This plan is the base plan upon which the other two alternatives are developed. As seen in Figure 15, some of the major tasks are performed concurrently resulting in a slightly higher risk and increased cost but in less time duration.

The Shortest Time Plan is the plan which seeks to fulfill the technical requirements of the project in the shortest possible time.[4] As time is reduced, technical risk increases. The paralleling of activities in Figure 15

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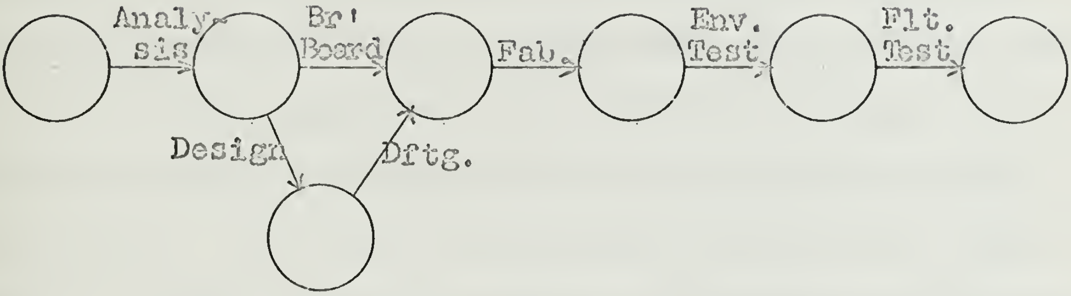
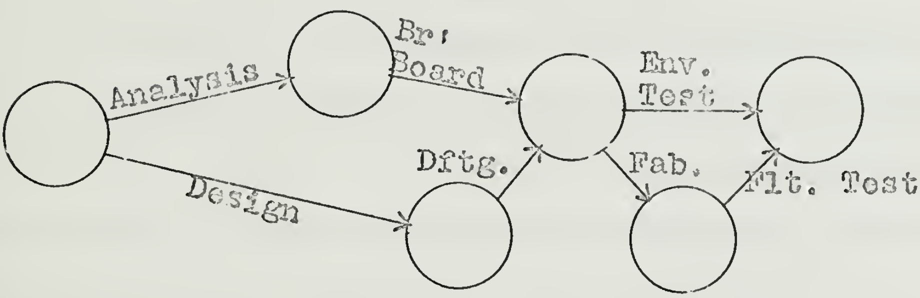
[1] Ibid., p. 102.
[2] Ibid.
[3] Ibid.
[4] Ibid.

Most Efficient Plan



Directed Date Plan



Shortest Time Plan

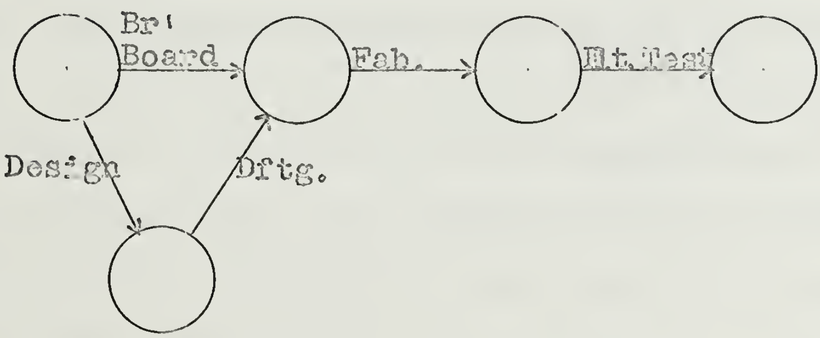


Fig. 15.--Time-cost option

Source: DOD and NASA Guide: PERT COST, p. 102.

reduces safety inherent in activities performed in series. If similar but not identical projects have been completed previously, activities may be eliminated, and decisions are made on knowledge gained from the completed portions. The use of nonspecific knowledge may be quicker but it entails greater risk. Costs for this plan may rise from the application of a higher level of effort on individual activities and increasing the number of activities performed in parallel. If activities are eliminated, project cost could decline but at the expense of increasing technical risk.

It is important to recognize that the Time-Cost Option Supplement is not a technique for optimizing the time-cost relationship in a project. It provides three time-cost-risk combinations from a range of possible alternatives from which the customer can make trade-offs of increased cost for decreased time and vice-versa.[1]

A more complex approach is the Resource Allocation Supplement. This approach assists the project manager in arriving at the most efficient project plan.[2] Whereas PERT/Cost is designed for application in the planning and controlling of an entire project, the Resource Allocation Supplement is designed for use in planning a small group of associated activities representing only a small portion of the overall project. This supplement rests on the assumption that activities

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[1] *Ibid.*, p. 104.

[2] *Ibid.*, p. 108.

in a network are subject to time-cost trade-offs.[1] Under this method various time-cost alternatives are constructed for each activity in a group of interrelated activities. Any number of meaningful time-cost combinations may be estimated by the responsible supervisor. The time duration of an activity is chosen as that for the lowest cost alternative. Then by selecting smaller activity times with their correspondingly higher costs on certain critical path activities, time is bought on the critical path until the desired combination is reached. In choosing which activities on the critical path to shorten, the slope or incremental time-cost relationship between estimates on each activity on the critical path must be determined. The slope is found by formulating a ratio of the increase in cost by the decrease in time that occurs when moving to the next lower time estimate.[2] Time will then be bought along the critical path on the activity with the smallest slope. This method results in the selection of the most efficient plan for reducing project duration to a pre-set target duration and is most useful on limited aspect networks, where the optimization of resources is attempted for only a small group of activities rather than for an entire project.

Advantages and Disadvantages

The advantages of the PERT System are many. The

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[1] Ibid., p. 109.   [2] Ibid., p. 111.

essence of the technique is planning. PERT methodology requires complete, systematic planning of the entire project from beginning to end. Each task of the project must be analyzed in light of the project as a whole. The outcome of this thorough planning requirement is a realistic plan which improves the chances for the accomplishment of the project objective. This is most beneficial in the pre-contract stage where PERT serves as a communications tool for directing the efforts of the potential team members in arriving at their consolidated proposal. By carefully and explicitly defining the initial Work Breakdown Structure, the team members from various organizational departments have a common foundation. Later, as the proposal develops, the PERT network provides a common point of reference.[1]

Further advantages to the bidder in the pre-contract stage are:

1. Provision for assessing the relative merits of alternative approaches.

2. Identifying key decision points and their associated deadlines when formulating the proposal.

3. Establishing manpower requirements and the rate of manpower buildup required throughout the program.

4. Determining the critical areas of effort and testing the effects of using additional resources or performing

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[1]Austin McHugh, Jr., "How to Write Better Proposals with PERT," Aerospace Management, January, 1963, p. 48.

parallel efforts on those areas to increase efficiency.

5. Defining tasks which must be started immediately to meet proposal deadline.[1]

By requiring bidders to support their proposals with PERT networks and resource estimates, customers gain an effective aid for the analysis and evaluation of proposals. This allows for a discipline to communicate the logic and reasonableness of proposed time schedules and resource estimates, a common structure for better comparison of time schedules and resource estimates, and a standard for the re-assessment of original target dates and resource requirements as set forth in the Request for Proposal. In preparing PERT networks for this stage many potential problems which could delay project accomplishment may be revealed so that early corrective planning action may be taken. Reevaluation prior to the operation stage can and often does result in a more efficient plan at less cost.[2]

In the operational stage of a program, PERT permits management-by-exception at all levels by focusing attention on those parts of the project that are most likely to prevent its success or prevent project completion according to schedule. Critical events which need continuous monitoring are highlighted,

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[1]Rene L. Eris and Bruce N. Baker, An Introduction to PERT/CPM (Homewood, Ill.: Richard D. Irvin, Inc., 1964), p. 49.

[2]Ibid.

thus affording early detection of potential problems. This permits concentration of executive skill where it will do the most good and eliminates much routine, unproductive effort. Continuous monitoring reveals information on poorly used resources thus promoting increased efficiency. By identifying real time and resource requirements, PERT permits detailed scheduling and supplies critical and non-critical areas with funds, manpower and resources. Under-used resources can be applied to critical areas thus making maximum use of men and materials.[1]

By periodically measuring actual accomplishments against scheduled plans, PERT permits reevaluation and rescheduling of operations so that objectives can be met on time with minimum additional expenditure. Alternative plans and schedules can be simulated without actually changing or disrupting the existing plans and schedules. This capability adds a measure of project control and evaluation with unlimited possibilities throughout the life of the project. The PERT/Cost feature of the periodic evaluation gives tighter cost control by permitting cost effectiveness evaluation of the work package and summary cost levels resulting in minimum costs and maximum profits.[2]

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[1] U. S., Department of the Air Force, Air Force Systems Command, USAF PERT/TIME Systems Description Manual (Washington, D. C.: Air Force Systems Command, 1963), pp. 1-4.

[2] Ibid.

PERT is not without disadvantages. One problem is poor application. A frequent complaint in this area is that PERT networks tend to be too complex and produce an overabundance of information which cannot be usefully digested.[1] These complaints may be true in individual cases, but they are largely due to careless, improper, or poor application. Large networks containing several thousand events are complex to anyone; a company that permits this is operating under the misconception that an entire program must be integrated into one gigantic chart. If the PERT network is to represent a plan for accomplishment of program objectives, the network must be easy to read and understand. The volume of computer printouts and unfamiliar data such as variances and standard deviations does represent an overabundance of undigestable information to the uninformed manager; consequently, PERT training for the manager is a prerequisite for its use. These shortcomings are faults in application and not weaknesses in the PERT system. Successful implementation rests on the education and cooperation of managers. PERT was designed as an aid for decision making to complement existing management techniques, not to replace them; therefore, PERT must be considered in its application in light of other existing management procedures and systems.[2] Individuals, executives, and

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[1]Walter Maynes, "What's Wrong with PERT?", Aerospace Management, April, 1962, pp. 20-25.

[2]Miller, Schedule, Cost, and Profit Control with PERT, p. 172.

supervisors must not be bound to old static methods of management when utilizing the dynamic PERT system.

Another complaint which appears to have some validity is that PERT time estimates are frequently inaccurate.[1] This is sometimes true, for a time estimate is only as good as the experience of the person making it. Furthermore, in certain areas of operations such as research and development where new products are being developed on the fringe of technological progress and state of the art, accurate time estimates are indeed difficult. However, even here some time estimate is better than none and PERT is the only management system which has a probability expression which shows the relative uncertainty of the time estimate.

Another complaint is the cost of implementing the PERT system.[2] While some PERT applications, particularly those that were poorly applied, may have proved rather expensive, studies of applications by large contractors put the cost of implementation of PERT/Time at 0.2 to 1.0 per cent, and PERT/Cost at 1 to 5 per cent of total program cost.[3] These same studies indicate, however, that over the life of the project, the resultant savings from PERT implementation more than compensate for the additional cost of the system.

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[1]Maynes, "What's Wrong with PERT?", p. 25.

[2]Miller, Schedule, Cost, and Profit Control with PERT, p. 61.

[3]Ibid., p. 121.

CHAPTER IV

PROJECT TIME-COST OPTIMIZATION

Background and Assumptions

There is an underlying philosophical assumption that time is money; that is, time can be converted into a monetary value and expressed as a unit of cost. For example, a man's wages are determined by his worth per unit of time of work. For a project, there is a definite relationship between the total cost of the project and its duration. If project duration is indefinite, then costs will continue indefinitely. If the project is expedited, costs will increase. This relationship is shown in Figure 16.[1] The essence of the

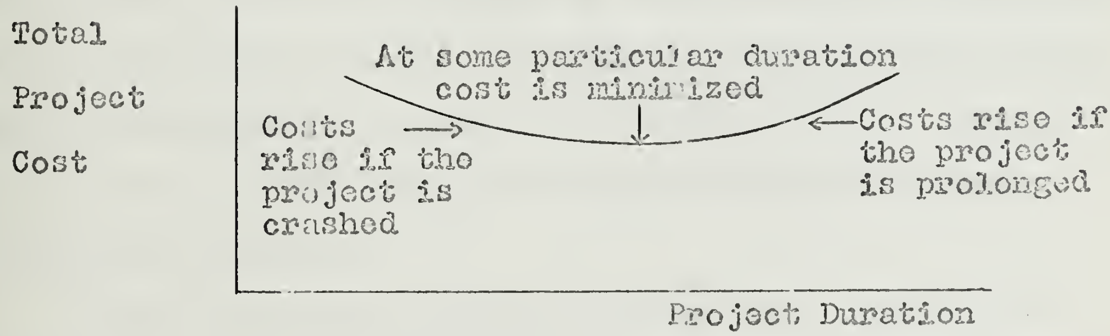

Fig. 16.--Project time-cost relationship

[1]Martino, Applied Operational Planning, p. 41.

relationship is that project cost is a measure of project resource expenditures; men, materials and time can be measured in terms of costs.

Slack time in a network-based system is "dead time" since most resources available for performing the associated activities are unavailable for use during that slack time. Along the critical path, the project plan requires a specific level of resource allocation to perform the job. With the critical path being the longest time path, there is inherent slack built into the other paths. Therefore, there is a direct variance between the time length of the critical path and other paths, the variance being slack time. There is then an economic trade-off which will perform the project most efficiently and thereby reduce the total project cost. It is reasonable to assume that activity completion times on the critical path can be reduced by the addition of resources (labor, equipment, or both). Whether the cost of these additions is economically desirable in relation to cost incurred is the essence of the time-cost trade-off and the decision of the project manager.

Time compression involves buying time along the critical path at minimum cost because a primary objective is determining the optimum allocation of resources among the activities to meet a required project duration or to create an optimum schedule. In considering the reduction of an activity's duration, the effects of increasing resources measured

by costs (capital outlay) on duration must be determined.

Total cost of a project can be classified as the sum of two separate costs--direct and indirect.[1] Direct costs are those that include items of direct labor and materials whereas indirect costs include supervisory costs and other overhead costs such as cumulative interest costs on the investment, and penalty (or bonus) costs for completing the project after (or before) a specified date.[2] It is generally acknowledged that the direct time-cost trade-off curve is a monotonic function with the dependent variable (cost) decreasing throughout its range as the independent variable (time) increases as shown in Figure 17.[3] In the time compression

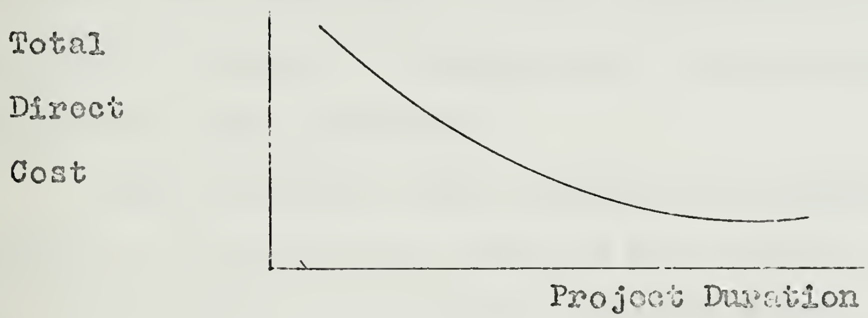

Fig. 17.--Convex time-cost curve

to be discussed in this paper, the following time-cost curve is assumed to be a piece-wise linear function (Figure 18)

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[1] Moder and Phillips, Project Management with CPM and PERT, p. 8.

[2] Ibid.

[3] Martino, Applied Operational Planning, pp. 42-43.

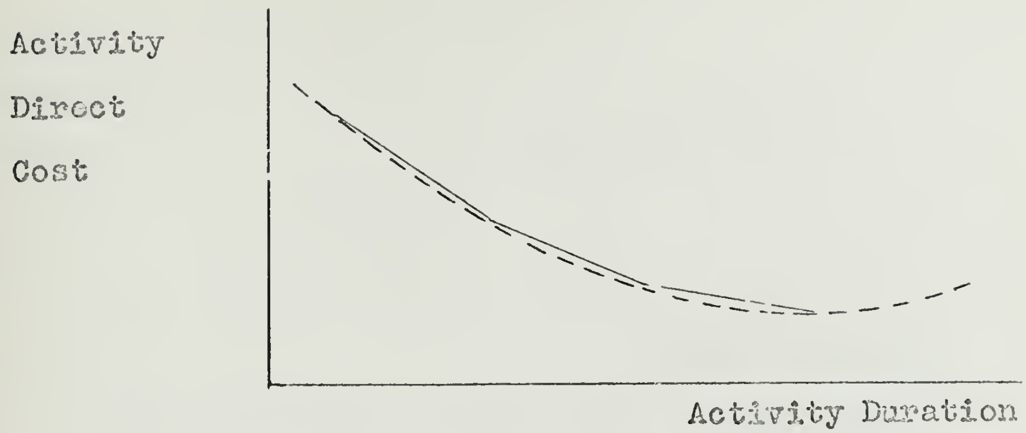

Fig. 18.--Piece-wise linear time-cost curve

which is a very close approximation to the convex time-cost curve of Figure 17.[1] It is further assumed that time-cost trade-off points will lie on this piece-wise curve and that activities are independent in that buying time on one activity does not affect the availability, cost, or need to buy time on some other activity.[2]

Indirect project cost increases as project duration continues. If supervisory overhead were the only indirect cost, the graphic representation would be a straight line function with the indirect cost line increasing with a slope equal to the daily overhead charge as illustrated in Figure 19.[3] However, when there are outage losses as a result of penalty costs for overrun, or losses on profits due to the

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[1]Moder and Phillips, Project Management with CPM and PERT, pp. 123-125.

[2]Ibid.

[3]Martino, Applied Operational Planning, p. 42.

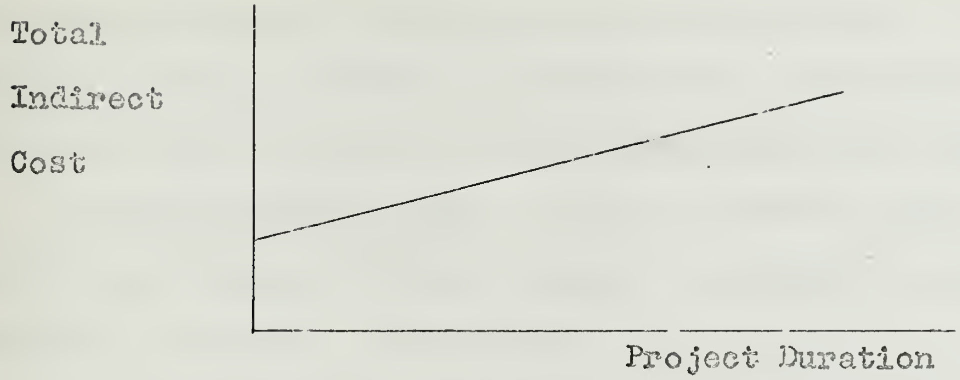

Fig. 19.--Total project indirect cost curve

inability to meet demand, then a corresponding cost increase must be added to overhead producing the curve illustrated in Figure 20.[1]

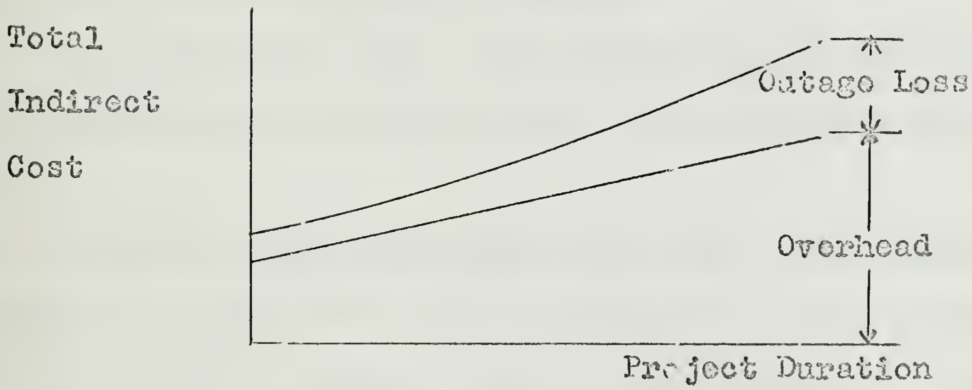

Fig. 20.--Total project indirect cost curve

In this paper it is assumed that project indirect costs can be determined by existing accounting procedures.

In order to understand time-compression procedures, the following terms are explicitly defined:

Activity direct cost: the cost of materials, equipment,

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[1]Ibid.

and labor required to perform the specific activity. If the activity is being performed completely by a subcontractor, the price of the subcontract is the activity direct cost.

Project indirect cost: project overhead costs to include supervision, interest charges on cumulative project investment, penalties, or bonuses.

Normal Time (NT): the shortest time required to perform the activity under the constraint of minimum direct cost.

Expedite Time (ET): the crash time or absolute minimum amount of time in which an activity can be accomplished.

Normal Cost (NC): the absolute minimum of direct costs required to perform an activity.

Expedite Cost (EC): the minimum direct cost required for accomplishing an activity under the constraint of minimum time.

Feasible time-cost points (FC, FT): any combination of time-cost points that can be scheduled. It is assumed that the choice made is optimal; that is, the direct cost associated with a stipulated activity time is the lowest possible direct cost for that time, and correspondingly, the activity time is the lowest possible for a stipulated direct cost.[1]

Schedule Time Compression Analysis

Under ordinary circumstances, a project would not be scheduled for a longer duration than normal duration time;

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[1]Moder and Phillips, Project Management with CPM and PERT, pp. 107-127.

however, a project may be replanned and rescheduled for a shorter duration time for one of the following reasons:

1. To decrease normal project duration for contractual purposes.

2. To obtain decision-making information on the extra cost incurred for possible project duration reduction.

3. To meet an arbitrary specified duration time, or to arrive at an optimal schedule for a project so as to minimize total project cost and maximize profits.[1]

The provisions for time-cost trade-offs included in the CPM and PERT network-based scheduling methods were discussed in Chapters II and III. Schedule time reductions for arriving at optimal project schedules can be made using CPM procedures discussed in Chapter II. Minor schedule time reductions for optimizing selected activities can be made using the Resource Allocation Supplement to the PERT method. The following time compression analysis is applicable to both CPM and PERT systems provided the assumptions previously listed are made. The results of application of the method will be relatively accurate and timely information which will aid project management in making decisions for project time-cost optimization. In performing a time compression, a total project cost curve is obtained by combining the project direct cost curve with the project indirect cost curve. The project

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[1] Ibid., p. 108.

total cost curve is a graphic representation of the ratio of change of cost to time. An optimal schedule time-cost relationship will exist on this curve and is defined as the schedule which satisfies all scheduling restrictions thus making it a feasible schedule and further produces a lower total cost than any other schedule making it optimal.

Beginning with a network-based time-oriented scheduling system, each activity is assigned a time for its successful accomplishment. These activity time estimates are of paramount importance in scheduling large projects and are based on the best experience and knowledge available at the time of the estimates to represent normal time as defined earlier. A corresponding expedite time is also determined at the same time as NT with associated direct cost estimates for each. The procedure in utilizing these estimates is to assume a linear relationship between the NT and NC point and the ET and EC point. If this is done, a piece-wise linear curve will result. The basis for project scheduling and time compression is the estimated time-cost function; therefore, erroneous estimates can result in a series of activities being termed critical when they are not.

Once time estimates are made, the critical path is selected using methods discussed earlier. Now each activity on that path must be analyzed to find which activity has the least time/cost ratio. The activity with the lowest ratio is reduced in time by a predetermined incremental amount.

The critical path is checked to insure that it remains critical. This procedure is continued until the critical path is maximized; that is, until the activities are reduced to their expedite times or another path becomes critical at which time the lowest time/cost ratio of the multiple critical paths is reduced. After each reduction, the new project direct cost is calculated and plotted on a graph. The ultimate desired result is shown in Figure 21. This desired result is the

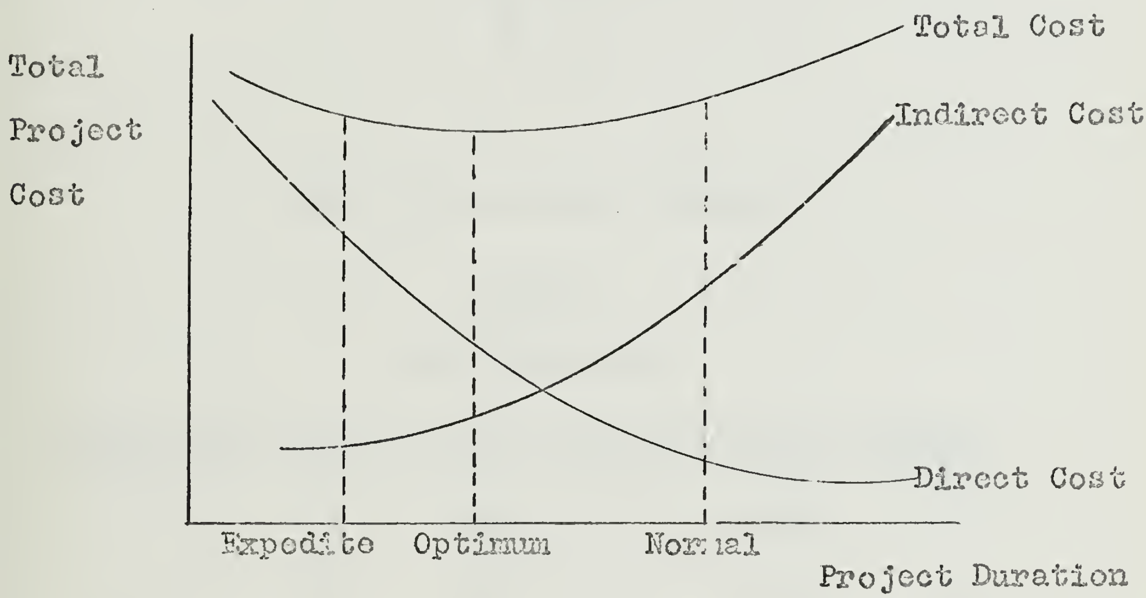

Fig. 21.--General project time-cost relationship

optimal project schedule which occurs at the point where total cost is least. This optimal schedule is then used to plan, evaluate, and control the project in the PERT/CPM manner described earlier.

As an example of the time compression procedure, consider the network below in Figure 22 with the data given in Table 3.

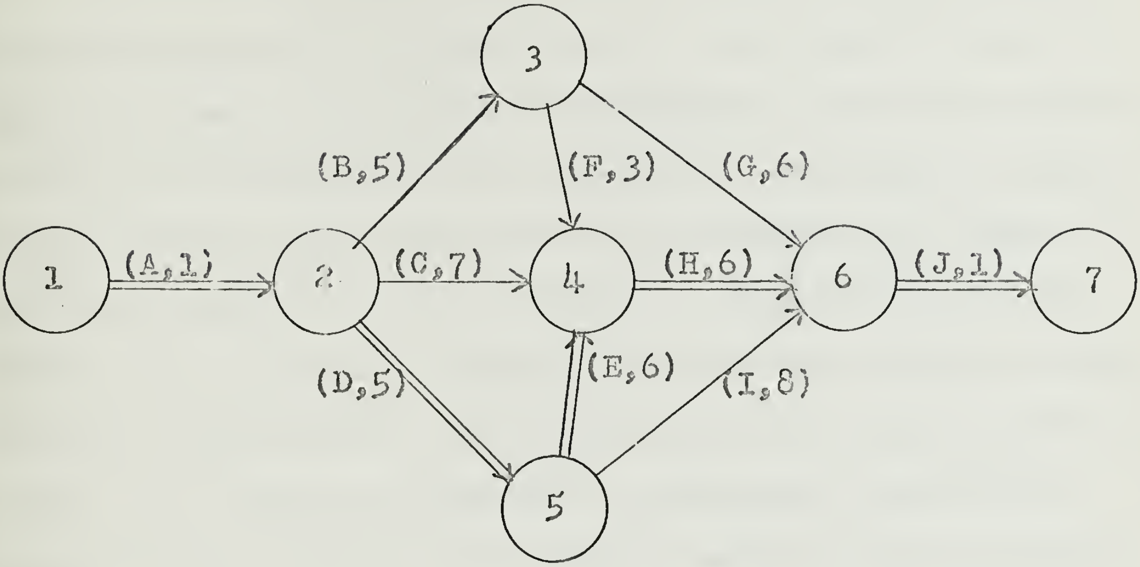

Fig. 22.--Project network

TABLE 3

COST-TIME DATA

Activity	NT	NC	ET	EC	ΔC/ΔT
A	1	200	1	200	--
B	5	300	3	400	50
C	7	400	5	800	200
D	5	500	2	980	160
E	6	200	3	500	100
F	3	700	2	800	100
G	6	600	3	1,200	200
H	6	300	4	400	50
I	8	500	5	650	50
J	1	200	1	200	--
		3,900			

The above network represents either a small project or a work package of a large project. The activity time estimates, direct cost estimates and critical path were arrived at using the methods discussed earlier. The reader is reminded that activity time-cost curves are assumed to be linear and continuous between NT, NC, and ET, EC. From Figure 22, the critical path is seen to consist of activities A-D-E-H-J with a project normal direct cost of $3,900, and a time duration of 19 days. If a time compression is considered, the project manager will be supplied with useful decision-making information for his use in arriving at an optimum schedule.

If a time compression in increments of one day is performed, then from Table 3 activity H on the critical path will give the minimum cost increase of $50 per day. Activity H can be reduced two days at a total direct cost increase of $100 before reaching its expedite time limit as shown in Figure 23.

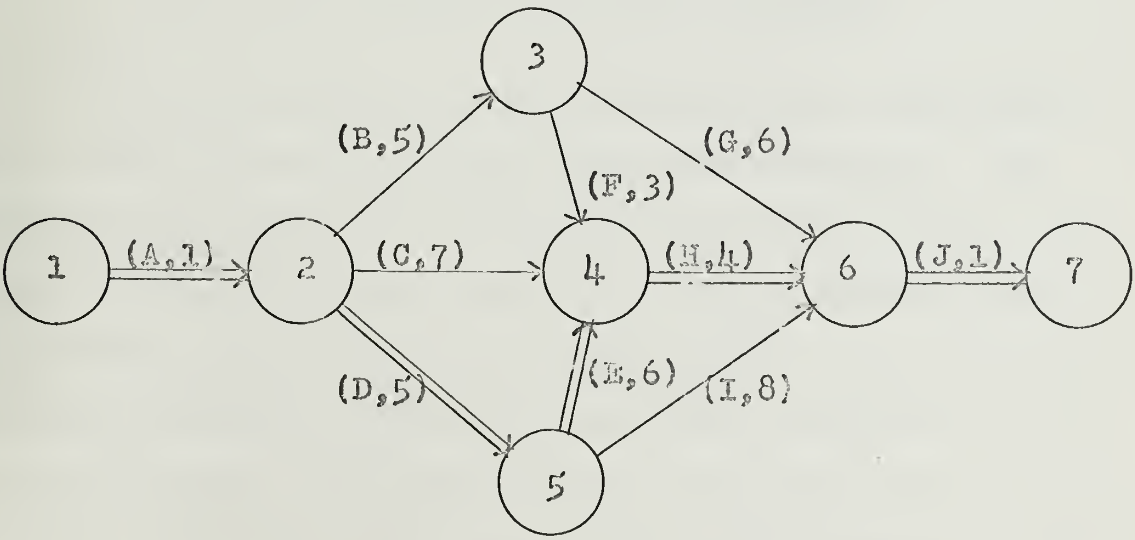

Fig. 23.--Seventeen day project schedule

Activity E now becomes the least cost activity for time reduction. It has a time-cost ratio value of $100 whereas activity D has a value of $140, while activities A and J cannot be reduced. Activity E can be reduced two days at a total direct cost increase of $200 before multiple critical paths are incurred as shown in Figure 24.

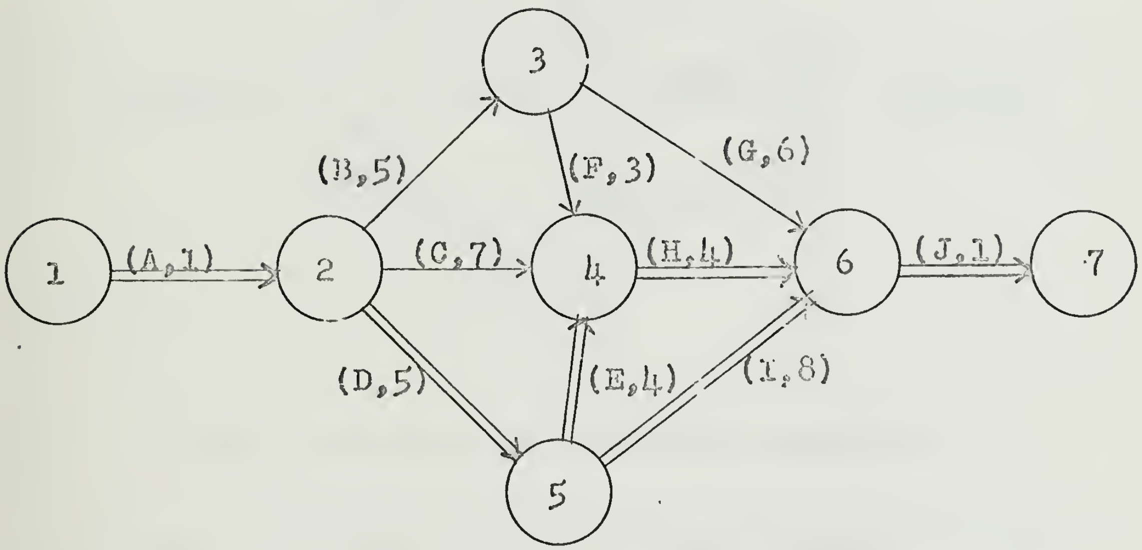

Fig. 24.--Fifteen day project schedule

At this point in the time compression, activities E and H form a parallel critical path with activity I. The possible time reductions of the critical path are now a dual reduction of activities I and E at a cost of $150 per day or a reduction of activity D at a cost of $160. Activity E can be reduced only one additional day before reaching its expedite time limit. Since the activity E-I cost slope is less than the activity D cost slope and therefore optimal, the E

[illegible]

[illegible]

[illegible]

and I activities are reduced one day, giving a fourteen day project schedule. At this point, multiple critical paths are again reached as shown in Figure 25.

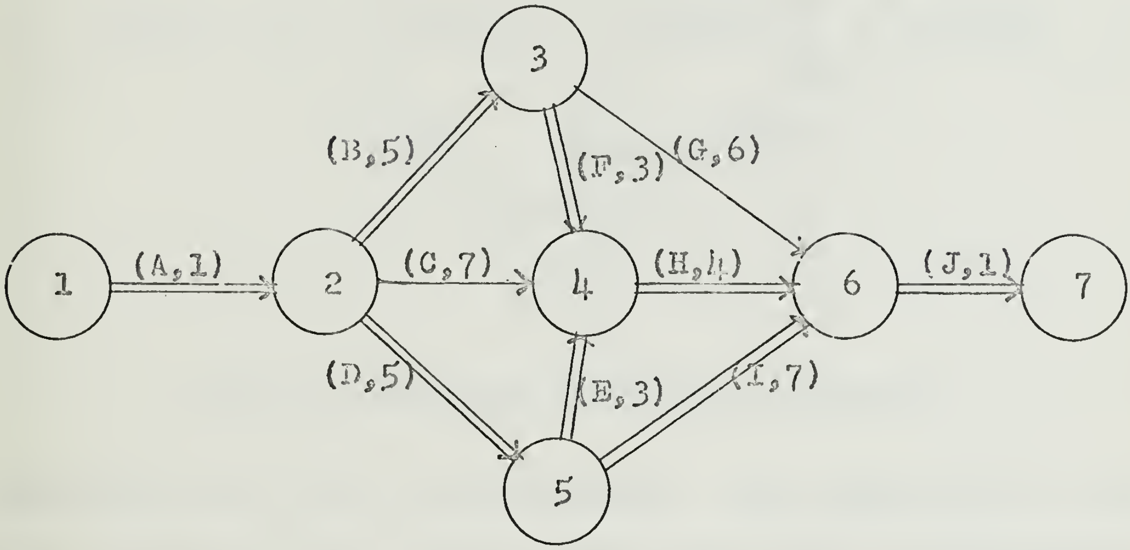

Fig. 25.--Fourteen day project schedule

Since activities E and H are both compressed to their expedite time limits, and activity I cannot be further compressed without removing it from the critical path, they are dropped from further consideration. Possible reductions in the critical path must now come from the combinations of activities B and D or activities D and F. The B and D combination has a cost slope of $210 while the D and F combination has a cost slope of $260. The B and D combination is optimal and reduced one day until further multiple paths occur as shown in Figure 26.

Possible further time reductions include the B-C-D

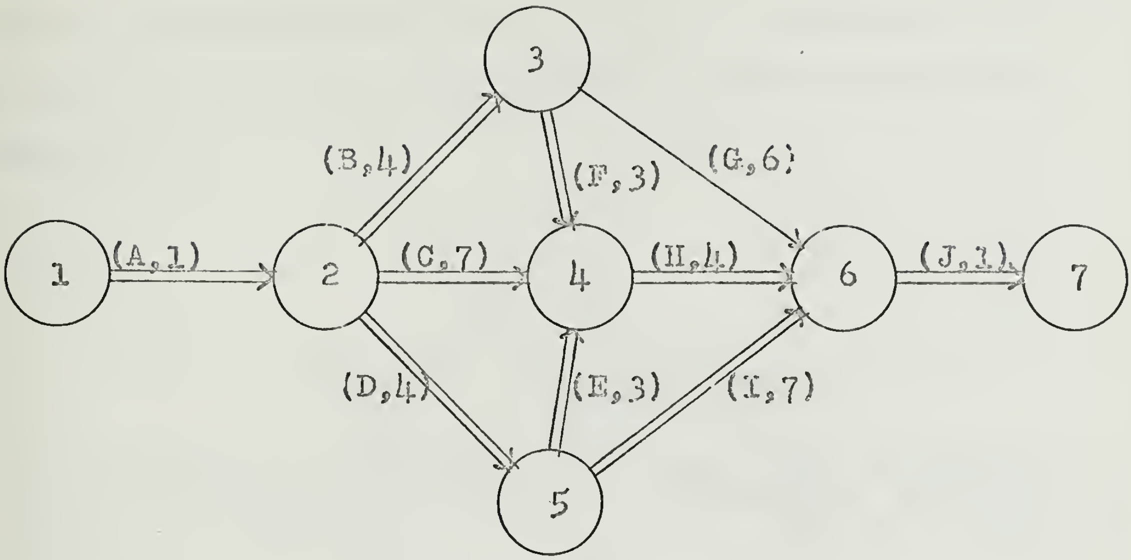

Fig. 26.--Thirteen day project schedule

combination and the F-C-D combination. The former has a cost slope of $410 and the latter, $460; the former, being optimal, will be reduced one day at which time Activity B will reach its expedite time limit and will be excluded from further consideration. One further reduction of one day of the activities F-C-D, which are the only remaining compressible activities in the critical path will result in an eleven day schedule. At that point activity D reaches its expedite time limit thus preventing further time compression of the network since the critical path of A-D-E-H-J is at expedite or crash time. The final network is shown in Figure 27 in which all paths are now critical.

The steps in the time compression are summarized in Table 4. For this example, it is assumed that an indirect cost of $5,000 for a nineteen day schedule is assigned to the

project work package with indirect costs increasing $100 per day for overages and decreasing $100 per day for duration reductions.

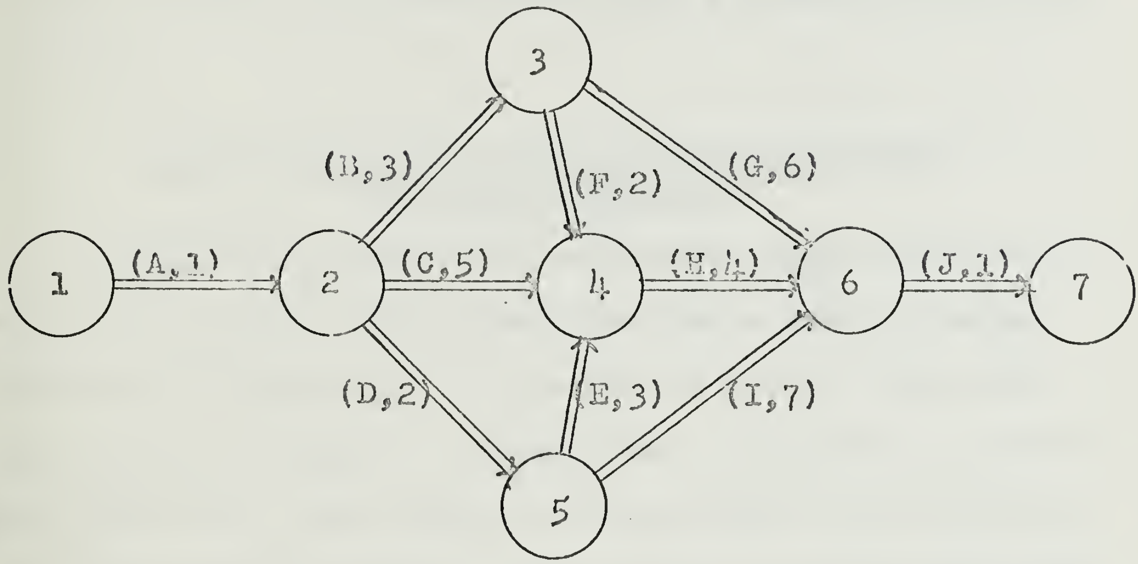

Fig. 27.--Eleven day project schedule

TABLE 4

TIME COMPRESSION DATA

Project Time	Direct Cost	Indirect Cost	Total Project Cost
19	$3,900	$5,000	$8,900
18	3,950	4,900	8,850
17	4,000	4,800	8,800
16	4,100	4,700	8,800
15	4,200	4,600	8,800
14	4,350	4,500	8,850
13	4,560	4,400	8,960
12	4,970	4,300	9,270
11	5,430	4,200	9,630

The information in the table would be invaluable to the project manager in making a decision as to the optimum project schedule. It can be seen for this example that the optimum duration is fifteen days with a minimum total cost of $8,800.

Resource Allocation Supplement Application to Time Compression

This time compression method was performed in the same manner as the CPM project duration reduction method discussed in Chapter II. It can be as readily used with PERT in one-of-a-type or research and development projects where there is a high degree of uncertainty in estimating normal and expedite times. The vehicle through which time compression can be applied is the Resource Allocation Supplement explained in Chapter III.

Since the Supplement is based on the premise that "activities" in a network are subject to time-cost trade-offs, selected time-cost conditions for least cost and least time with their respective time and cost complements can be ascertained.[1] The basis of the premise is the assumption that activities can be performed or accomplished in one or more ways with the alternative ways having varying time durations and direct costs. By applying this technique normal time, normal cost, expedite time and expedite cost values, consistent with the definitions of these terms stated earlier in this chapter,

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[1] DOD and NASA Guide: PERT Cost, p. 109.

are easily obtained. Once these values are determined, the time compression can proceed as described.

Project Time-Cost Curve Analysis

The time-cost curve in the time compression method was assumed to be a continuous piece-wise linear function. This curve, with its corresponding assumption, is actually quite accurate.

The actual relationship between activity direct costs and time is a convex curve as shown in Figure 28.[1]

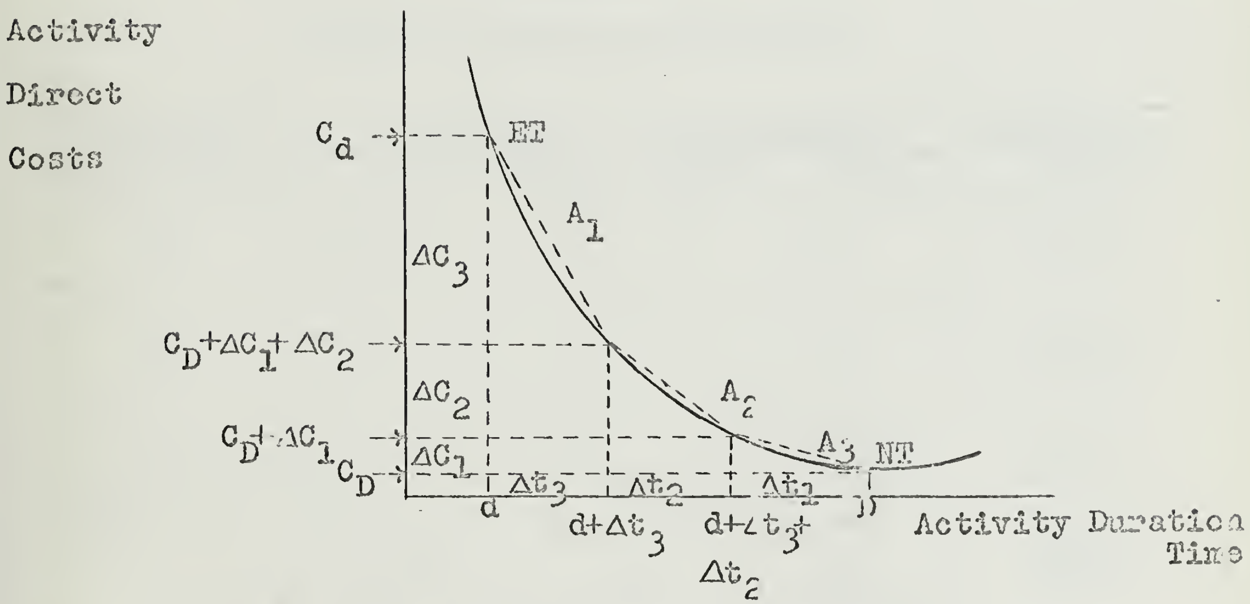

Fig. 28.--Piece-wise linear approximation to convex time-cost curve

The curve is convex or downward sloping to the right following the law of downward sloping demand.[2] Thus, if a minimum time

[1]Moder and Phillips, Project Management with CPM and PERT, p. 124.

[2]Paul A. Samuelson, Economics: An Introductory Analysis (6th ed.; New York: McGraw-Hill Book Company, 1964), p. 59.

constraint is placed on an activity with limited resources available for its completion, the cost of the activity increases. In Figure 28, the actual curve is approximated by a piece-wise linear curve with each piece being treated as a separate activity or pseudo-activity. The actual activity, A, in the project network, is replaced by three pseudo-activities, A_1, A_2, and A_3 drawn in series. The normal and expedite time-cost point coordinates for each pseudo-activity are given in Table 5. The sum of the pseudo-activities,

TABLE 5

PSEUDO-ACTIVITY COMPUTATIONS

Pseudo-Activities	Normal		Expedite		Time-Cost Slope
	Time	Cost	Time	Cost	
A_1	$d+\Delta t_3$	0	d	ΔC_3	$\Delta C_3/\Delta t_3$
A_2	Δt_2	0	0	ΔC_2	$\Delta C_2/\Delta t_2$
A_3	Δt_1	C_D	0	$C_D+\Delta C_1$	$\Delta C_1/\Delta t_1$
Total: A	$D=d+\Delta t_3+\Delta t_2+\Delta t_1$	C_D	d	$C_d=C_D+\Delta C_1+\Delta C_2+\Delta C_3$	$\frac{(C_d-C_D)}{(D-d)}$

A_1, A_2, and A_3, gives the whole activity, A, and the sum of the coordinates of the normal and expedite points for the pseudo-activities gives the coordinates of the same points for the whole activity.

In a time compression, time reduction is begun at the normal time and cost point, or coordinates (D, C_D) in Figure 28; thus, all pseudo-activities or pieces emanate from this point. As the time compression progresses, the pseudo-activities are taken in the order of least cost or increasing cost-slopes.

The accuracy of the piece-wise linear approximation has been proved through experience gained from years of use by such agencies as the National Aeronautics and Space Administration and C-E-I-R.[1]

Even though the results of the linear assumption are quite accurate, it must be remembered that in compressing time if the straight line relationship is not valid then the compression sequence would not be performed at minimum cost. If the assumption is valid and the approximation is very close to actual values, then an optimal schedule will result. An absolute optimum schedule cannot be obtained unless the true time-cost function for project direct cost is known. A true time-cost function has not yet been formulated and will not be formulated until the activity cost factors related to time and the resultant activity direct costs are studied and defined.

Time Compression Problem Areas

Though a time compression may be accomplished to

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[1] The CALC System (Bethesda, Md.: C-E-I-R, Inc., 1968), pp. 29-34.

successfully optimize a schedule using assumed relationships, there are shortcomings to the method. One problem is that of resource limitation or scheduling to a resource limit. This situation occurs when manpower, materials, or equipment is limited causing an upper boundary limit to be placed on manpower, equipment, or materials available for project scheduling. When resource restrictions limit the activity expedite time close to or equal to the activity normal time, then this restriction could be the determining factor for the critical path and unduly extend project duration. When this occurs, a time compression will not be a very beneficial tool because it does not provide for this problem. The task facing the project manager is that of reassigning resources from slack activities to the critical path so as not to exceed the resource limit.[1]

A second problem not provided for is that of resource leveling with a constraint on total project duration time. This problem involves the fluctuations in resource needs from one time period to the next. For example, if for a particular project the manpower requirements per unit time are summed along the project network, the manpower loading chart in Figure 29 results.[2]

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[1]Moder and Phillips, Project Management with CPM and PERT, p. 93.

[2]Miller, Schedule, Cost, and Profit Control with PERT, p. 115.

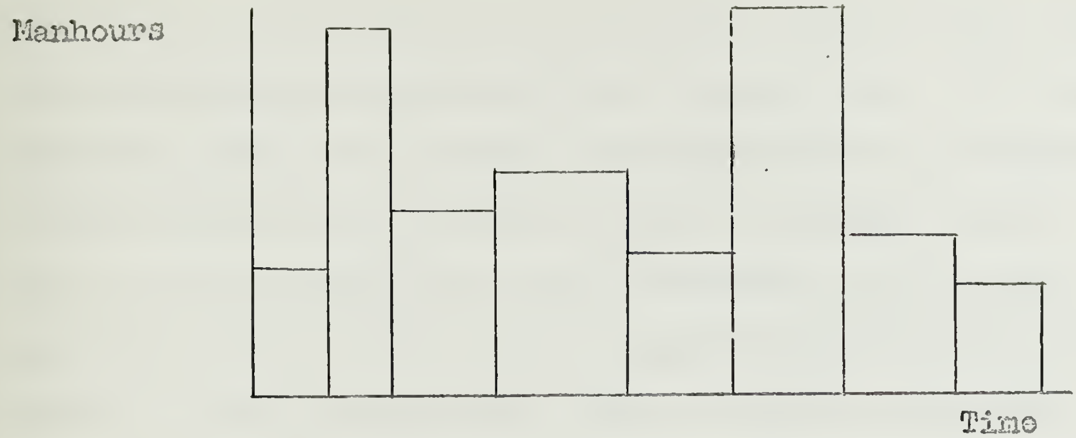

Fig. 29.--Manpower loading chart

Most organizations, large and small, cannot tolerate such large fluctuations of manpower during a single project life span. This is certainly true qualitatively if manpower requirements are heavily weighted toward professional employees such as scientists and engineers who are generally not available for intermittent short periods of employment. The obvious desired level of resource utilization would be a slow buildup at project commencement with a gradual decline toward project termination.

The problem reduces to the continuous, efficient use of resources throughout the life of the project. Resource needs from one time period to the next are not independent because a project may demand the use of key resources such as experienced supervisory personnel, specially skilled tradesmen, and particular types of equipment throughout the time frame and in various activities simultaneously.[1] This

[1]Riggs and Heath, Guide to Cost Reduction through Critical Path Scheduling, p. 128.

demand must be kept within the available supply at the same time satisfying the constraints of time and cost. The time compression does not consider this but leaves the resource leveling problem to be resolved after an optimal project time-cost relationship has been established. If resource constraints prevent the project manager from utilizing the results of a time compression, then an optimum time-cost project schedule is a dream.

One other shortcoming in the time compression provision is its failure to consider the optimum use of slack time for an activity. When an activity is begun, funds for that activity must be committed. Here, a dichotomy in project time-cost optimization via time compression exists: optimum cash flow would suggest delaying the start of an activity as long as possible without delaying the project, thus obtaining the maximum utilization of organizational capital. The problem of optimum cash flow and its determination is fundamentally in opposition to that of optimum project timing. With cash flow, project management prefers to spend funds as slowly as possible while maintaining a predetermined amount of progress, and, from a timing standpoint, to finish each activity as quickly as possible.[1] Project management must therefore make a preference for the location of slack in an activity. This

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[1]A. W. Wortham, "Project Cash Flow and Probabilistic Cost Determination" (unpublished paper, Department of Industrial Engineering, Texas A & M University, 1965).

preference cannot always be made, however, because the problems of resource leveling and scheduling to a resource limit may dictate the location of slack. In either event, time compression reduces slack time by shortening the critical path. As the time compression progresses, slack throughout the project is reduced, thus resulting in the possible commitment of activity funds earlier in time. The cost of funds needed to finance the activities and complete the project are included in the project indirect cost. However, an analysis of indirect cost rates per unit time measured against possible savings of investment costs due to delay of activity start times is not made. It is possible that savings in investment costs may exceed savings incurred by compressing the schedule a unit of time thereby saving one unit of indirect cost per unit time.

The time compression provision may consider this problem but only after the compression has been performed. Since funds are not usually available in one lump sum to cover the entire project, the funding schedule should be considered as an integral part of the time compression process. If this consideration is not made, the project may not be performed at minimum cost.

It is the purpose of this report not to present solutions to the problems of resource leveling, scheduling to a resource limit, and optimum use of activity slack time, but to indicate that these considerations are shortcomings in

the provisions for time-cost trade-offs toward project scheduling optimization by means of time compression. Indeed, these considerations are a hinderance to the development of better time compression techniques.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

At the beginning of this report it was stated that the three fundamental tasks of a project manager were recognition of a goal, organization of resources for goal accomplishment, and performance measurement. To control a project, all three tasks must be coordinated into a master plan which will complete the entire project in the best time, at the least cost, with a minimum of risk. This master plan must be flexible and dynamic to provide for: immediate revision or update should such be necessary; simulation of alternatives in cost and time in arriving at the best plan; evaluation and communication of alternative estimates. The PERT and CPM network scheduling techniques discussed in this paper are instruments which provide management with the means for accomplishing these fundamental tasks.

An attempt has been made to trace the development of network-based scheduling systems. The historical development of the Critical Path Method and the Program Evaluation and Review Technique was presented with emphasis on basic principles, methodologies, and provisions for time-cost trade-offs.

Only these two systems were discussed because all existing network systems have originated from them. The significant distinction between these two systems is the method of deriving activity time estimates. Several governmental agencies, notably NASA, have combined these two systems under the general title of PERT by using a single activity time estimate characteristic of CPM.[1]

The advantages and disadvantages of CPM and PERT were listed and analyzed in light of their benefits and limitations. The provisions for time-cost trade-offs included in these systems were reviewed and appraised. A critical analysis of significant assumptions, benefits, and shortcomings of a schedule time compression as a means for realizing an optimum project time-cost relationship was conducted and a time compression was illustrated. In doing this, the critical path of a small project was found using CPM/PERT methods. Each activity on that path was analyzed to find which had the least time/cost ratio. The activity with the lowest ratio was then reduced in time and the critical path again checked. This procedure continued until the time reduction on the critical path was maximized. Each time a reduction was made the cost of the reduction was tabulated. These costs, when added to project indirect cost, yielded project total cost figures. These costs when plotted produced a total cost curve from

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[1]Moder and Phillips, Project Management with CPM and PERT, p. 7.

which the optimal project time-cost relationship could be determined. This condition occurs at the minimum point on the curve and represents the point where the greatest time benefit is received for the least total project cost.

Conclusions

The applicability of existing network systems must be determined. The evaluation of a program that is in operation is an important and difficult task for project management. Network scheduling systems like PERT and CPM must be evaluated as programs by project management in light of their operation as management information and decision-making systems. These systems are not panaceas. They will not in themselves produce profit. They cannot be picked up in their entirety from textbooks or manuals and installed without adaptation to the organization's needs. No network scheduling technique is universally applicable. These systems must be modified and integrated with other management information systems currently existing within a company. Once integrated, the systems are most valuable as decision-making tools. They should not be used primarily as a means of providing historical data for evaluation after the fact, but as a means of providing information for decision making beforehand, at the point of action. These systems supply a means for thorough and reliable planning and control by allowing a visual presentation of progress to those who must make decisions.

As a result of this study, the following conclusions are reached concerning the provisions for time-cost trade-offs included in network-based scheduling systems and how they can be applied for project time-cost optimization.

There is a direct relationship between project duration and total project cost. When project duration is reduced to a minimum, project costs increase to a maximum. Project total cost is the sum of project direct costs and project indirect costs, thereby relating total cost to time.

The assumption that a continuous piece-wise linear direct cost curve is a close approximation to the actual convex direct cost curve is acceptable. By consenting to this assumption, it is expected that time-cost trade-off points will be on the piece-wise curve. The danger of this acceptance is obvious; if erroneous points are selected, activities could be termed critical when they are not and a minimum total project cost would not be reached.

Both PERT and CPM provide the means for identifying time-cost trade-offs. By using the CPM project duration reduction measures and the PERT Resource Allocation Supplement, a project time compression can be performed on any project network. The time compression method includes the best features of PERT and CPM and offers a means for project time-cost optimization.

The assumption that activities are independent in a project network to the degree that buying time on one activity

does not affect the availability, cost, or need to buy time on some other activity is acceptable only in a restrictive sense. It was shown that the time compression method does not consider the problems of resource leveling, and scheduling to a resource limit until after a time compression has been completed. Therefore, these problems could be the determining factors of the critical path and could unduly extend the project duration. The result of such an extension is that an optimum project time-cost schedule cannot be determined; however, an optimal schedule under the imposed restrictions can be determined. If the restrictions are too severe, the benefit of a time compression will be negligible.

A serious shortcoming of the time compression method is its failure to include provisions for project cash flow through the optimum use of slack time. Depending upon project duration and the time unit used in the time compression, large exaggeration in indirect cost rates could be made and used which would result in something more than minimum project cost. It could be that project cash flow through the optimum scheduling of slack time would result in a total project cost less than that achieved by the time compression method.

When its assumptions are satisfied, the time compression method is a most powerful tool for project management which will result in increased project efficiency and cost control. Although it does not provide the project manager with the optimum project time-cost schedule, it does provide

him with a means for obtaining an optimal schedule, thus greatly reducing total project cost. Should a method be developed which includes considerations for resource leveling, scheduling to a resource limit, optimum use of slack time for project cash flow, and a true time-cost function, then a time compression method could yield the optimum project time-cost schedule. It is entirely conceivable that eventually computer programs will be written which will include all of these considerations and will optimize all aspects of a project. The developments which can be expected in the future should significantly increase the flexibility and utility of computer programs. More realistic time-cost trade-off procedures and more complete allocation routines should evolve.

The choice between using a computer and manual methods is mainly a question of cost and convenience. Each project is different; therefore, a definitive answer is difficult. However, it is readily apparent that the use of computers greatly extends and expands the value of the time compression method for project time-cost optimization. After all, network analysis was developed as a computer oriented project planning, scheduling, and control technique. It is only logical that further refinements in network analysis will also be largely computer oriented.

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